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SPECTROCHEMICAL ANALYSIS

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In an industry of any size there are always chemical analyses to be carried out, both for testing the raw materials required for manufacture and for various tests during the process of manufacture, as well as for purposes of scientific research. Apart from ordinary chemical analysis, spectroscopy is also applied, whereby the substance to be examined is placed in a flame, a spark or a carbon arc and caused to emit light. In this article a method of spectrochemical analysis is described in which the carbon arc is employed.

Introduction

When an element in gaseous form is heated to a high temperature or subjected to an electric discharge it radiates light consisting of a number of radiations of very specific frequencies characteristic for the particular element. When the light is examined with the aid of a spectroscope or spectrograph a number of sharply defined lines (spectral lines) are seen which together form the spectrum of the element.

The study of these spectra is of great importance in physics because it has given a deeper insight into the structure of the atom. Chemistry, too, has profited from this study, in that the spectrum constitutes a sensitive mears of identifying the kinds of atoms.

At first the spectroscopic method was used for a qualitative determination of the presence of a certain element, but at a later stage, as was understandable, attempts were made to use spectroscopy for quantitative analysis.

Kirchhoff and Bunsen, who, about 1860, first pointed out the importance of spectroscopy in chemistry, caused various elements to emit light by vaporizing a small amount of a compound, for instance a salt or an oxide, in a colourless gas flame (the Bunsen burner). Nowadays, for quantitative analysis, electric discharges in the form of a spark or an arc are frequently used, in addition to flames.

In this article a method of quantitative spectrochemical analysis will be described which employs a carbon arc fed with direct current. A weighed quantity (a few mg) of the sample to be tested is fully vaporized in the positive crater and the spectrum of the light emitted during this vaporization is photographed. From the blackening on the photographic plate caused by the various spectral lines it is possible to deduce the concentrations of the components of the sample. This method has been worked out to a routine method which is as accurate as and quicker than the ordinary chemical analysis.

Before proceeding to describe this method it is well to consider the ways in which a spectrum can arise.

The formation of a spectrum

The energy level diagram

The frequencies characteristic for an element can be plotted in what is known as an energy level diagram. As an example the energy level diagrams of the mercury atom and the neon atom are given in *fig. 1*, where the horizontal lines represent the energy levels for a number of stationary states (excited states) of the atom in question.

For the sake of clarity the higher energy levels have been omitted. These higher levels converge upon a certain limit, called the ionization energy, corresponding to the energy required to seperate the optical electron from the atom in its normal states.

The vertical lines denote "transitions" between the energy levels. According to **Bohr** (1913), in the transition from a state with energy E_1 to a state with energy E_2 ($<E_1$) a light quantum is emitted with the frequency ν, such that

$$h\,\nu = E_1 - E_2\,. \qquad (1)$$

where h represents the **Planck** constant. Inversely, an atom in the state with energy E_2 can pass, through absorption of a quantum of radiation of the same frequency ν, into the state E_1. The energies E_1 and E_2 are mostly measured from the ground level corresponding to the normal, non-excited state of the atom.

Putting $E = eU$, where e ($= 1.602 \times 10^{-19}$ coulomb) is the charge of the electron and U is the potential difference (in volts) that an electron originally at rest has to pass to get a (kinetic) energy E, then, considering the values of h ($= 6.625 \times 10^{-34}$ W sec^2) and c (velocity of light $= 2.998 \times 10^8$ m/sec), the relation between the potential difference $\Delta U = U_1 - U_2$ and the wavelength $\lambda = c/\nu$ is:

$$\lambda \cdot \Delta U = 12{,}395\ \text{Å} \cdot \text{V}\,.$$

In accordance with the interpretation of the energy level diagram, to cause an atom to radiate light with a certain frequency it has to be excited with an energy equal to the value E_1 of the starting level. Except that E_2 together with E_1 determines the frequency — according to eq. (1) — the value of E_2, the energy of the final level, does not play any part here. The truth of this statement has been conclusively confirmed by the experiments carried out by **Franck** and **Hertz** [1]). *Fig. 2* gives an example of this. Electrons having a constant velocity v obtained by causing them to traverse a potential difference U, so that

$$\tfrac{1}{2}\,m\,v^2 = e\,U\,,$$

are shot into a space containing neon, under a pressure of 0.5 mm, and a little mercury vapour. An atom can be brought to a state with energy E_1 if

$$eU \geqq E_1\,. \qquad (2)$$

In accordance with the diagram in fig. 1, with increasing U there appear first the mercury lines in

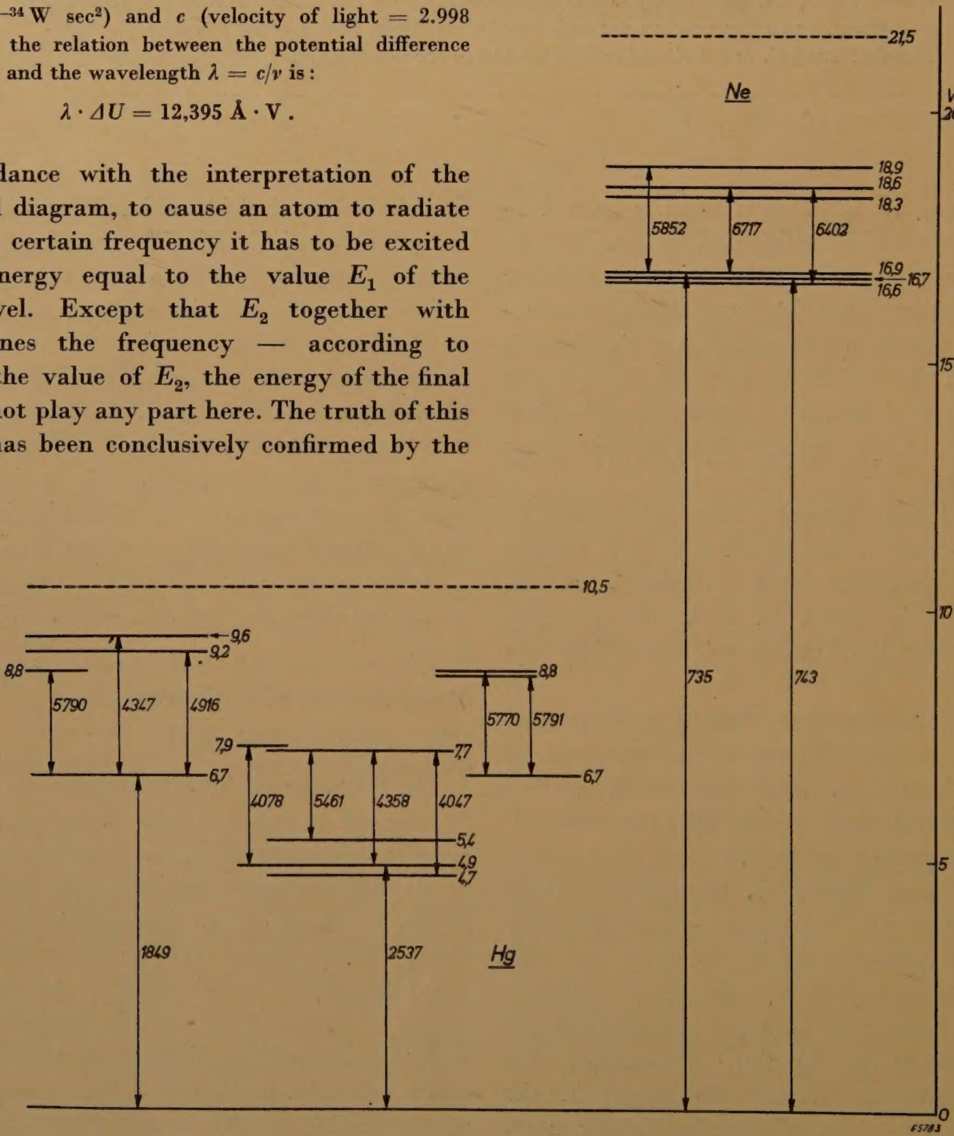

Fig. 1. Energy level diagram (incomplete) of mercury (Hg) and neon (Ne) with some transitions. The wavelengths corresponding to the transitions are given in Å.

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[1]) See, e.g., Handb. d. Physik (**Geiger und Scheel**) Bd. 3, I, 23—184, Springer, Berlin, 1933.

order of their initial levels and then the red neon lines.

This method of obtaining a spectrum with the aid of electrons with constant velocity is of great value when investigating the "structure" of a spectrum. For chemical analysis, however, it is less suitable.

rium is brought about by a number of pairs of antagonistic processes [2]), viz :

1) absorption and emission of light;
2) formation and destruction of excited atoms through collision with electrons;
3) ditto through collision with other atoms or molecules that may be present.

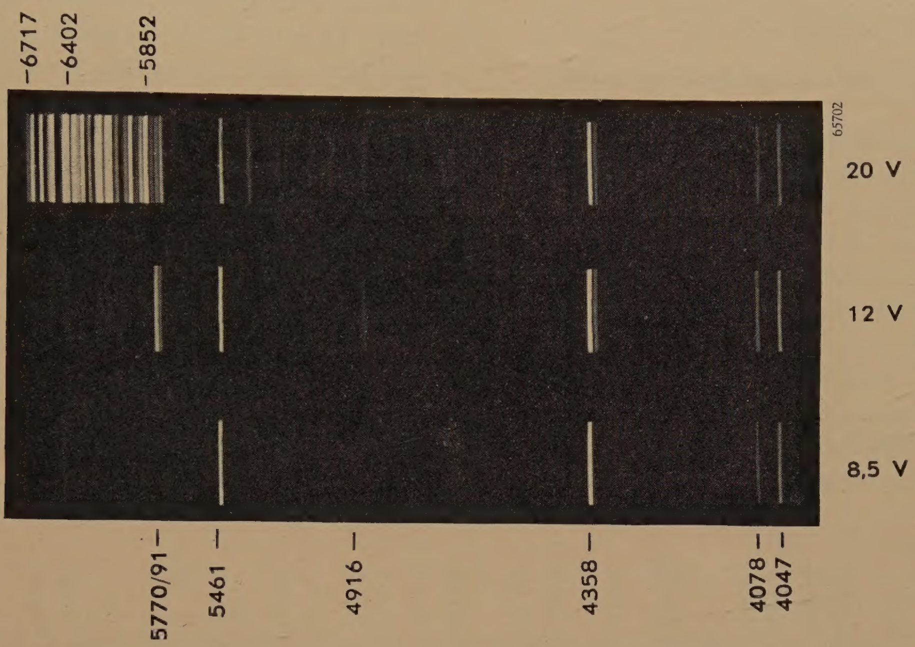

Fig. 2. Spectrum of a mixture of mercury and neon bombarded with electrons accelerated by voltages of 8.5 V, 12 V and 20 V. The weak lines on the left in the spectra for 12 V and 8.5 V are neon lines produced by scattered light from a part of the test tube in which fast electrons are present.

Furnace spectra

A spectrum can also be obtained by introducing an element in the gaseous or vapour form into an entirely closed space the walls of which have been brought to a constant temperature T. Thermodynamics teach us that in this case conditions are entirely determined by the value of T and that the number of atoms of a certain kind, in a state with energy E, is given by

$$\frac{n_E}{n_0} = \frac{g_E}{g_0} \mathrm{e}^{-E/kT} \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

where n_E is the number of atoms in the excited state and n_0 the number of atoms in the ground state; the g's are the weight factors characterictic for the element and for the respective states, which factors are small integer numbers.

From the kinetic point of view this state of equilibrium is brought about by a number of pairs of antagonistic processes [2]), viz :

Suppose a small opening is made in two opposite walls of the enclosed space so that one can see through it, or, as King [3]) did, a furnace is used (see *fig. 3*) in the shape of a tube open at both ends and with its wall brought to a constant high temperature. Then, upon a substance, say iron, being vaporized in that space or tube one can see the spectrum of that material appear. The intensity of each spectral line is proportional to the number of excited atoms n_E. Upon the temperature being raised the number of atoms with higher energy increases. At low temperature only the lines starting from levels with low energy are to be seen. An example of this is given in *fig. 4*.

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[2]) It is to be stressed that, according to the principle of detailed equilibrium, each pair of antagonistic processes is in itself capable of bringing about the equilibrium. See, e.g., M. J. Druyvesteyn and W. de Groot, Physica **12**, 153—166, 1932.

[3]) A. S. King, Astrophys. J. **27**, 353, 1908.

In order to predict how different elements will behave in this respect, a table of ionization voltages can be used; the ionization energy $E_i = eU_i$, as upper limit, is a rough measure for the excitation energy. Such a table is given below (*table I*) and graphically represented in *fig. 5*, from which it is seen that the ionization voltage U_i of most elements lies between 6 and 10 volts. Ionization potentials less than 6 volts occur in the case of alkali metals and further for a few elements such as Sr, Ba, La, Hf, Ra and U, thus mainly in the left-hand bottom corner of the table. Ionization potentials higher than 10 volts are found in the case of the rare gases, the halogens and the elements O, S, N, P, As, C and Hg, thus mainly in the right-hand top corner of the table.

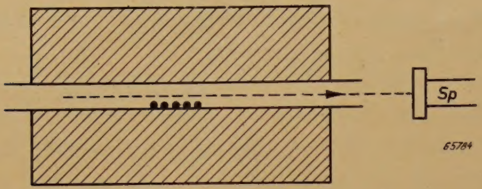

Fig. 3. King's furnace. Sp= spectograph.

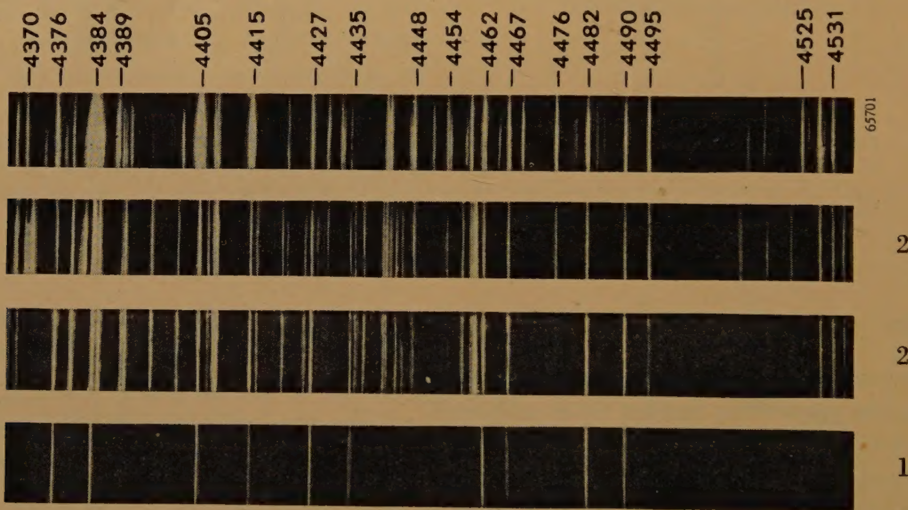

Fig. 4. Photographic record, according to King, of the spectrum of iron at three temperatures. Above these, the arc spectrum of iron is shown.

With the exception of the elements mentioned, therefore, most kinds of atoms will be visible at about the same temperature. A temperature of 2000 to 3000 °K is sufficient.

The flame

Instead of heating them in vapour form in a furnace, the elements can be exposed to a high temperature in a flame which in itself is not luminous. The same processes as mentioned above will take place likewise in the flame; the pairs of processes (2) and (3) will be fully active, but not so the pair (1), because though there is radiation outward there is no radiation inward. It can be proved, however, that the latter has little effect upon the equilibrium as a whole, so that the intensities depend upon the temperature in much the same way as in the case of the furnace. The temperature of the flame from an ordinary Bunsen burner is not particularly high, about 1700 °C, so that it is suitable only for elements which are readily evaporated and have a relatively low ionization voltage. In spectrochemistry special flames are now often used which are fed with a mixture of gas and oxygen and with which higher temperatures are reached.

Electric discharges at low pressure

Apart from exposing a gas or vapour to a high temperature, it can be caused to emit light by means of an electric discharge, as intimated when referring to the experiments of Franck and Hertz. Here a distinction has to be made between discharges under low pressure and with low current density (Geissler tube) and those under high pressure and with high current density (arc and spark).

Discharges in gases of low pressure have played an important part, for instance, in the discovery of the rare gases. The use of gas discharges of low pressure for generating spectra [4]) is almost as old as that of the Bunsen flame. Mostly the discharges have a positive column, in which the electrons are accelerated, but no farther than to the velocity at which they have gathered sufficient energy to excite and ionize atoms. Thus there is a limit to which the electron energy can be raised. As a result the velocity distribution appears to correspond to Maxwell's distribution with a fictitious temperature T_e (electron temperature). This temperature is of the order of 1500 U_i and thus,

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[4]) See, e.g., W. Elenbaas and J. Riemens, Light sources for line spectra, Philips Techn. Rev. 11, 299—302, 1950 (No. 10).

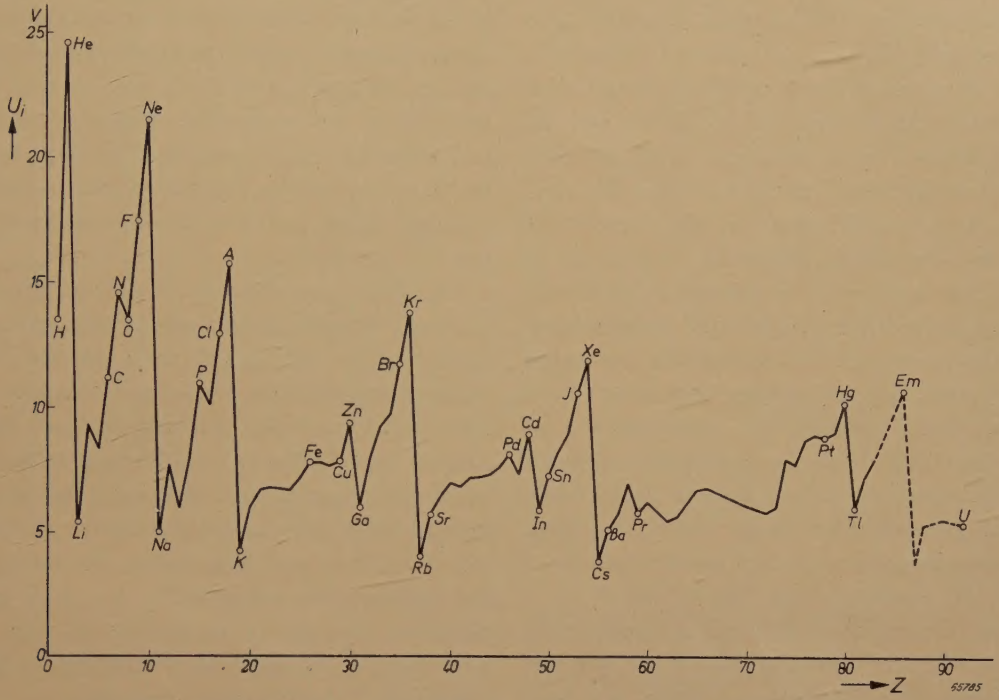

Fig. 5. The ionization potential U_i of the elements, plotted as a function of their atomic number Z.

Tabel I. The chemical elements arranged according to the periodic system. Above each element is the atomic number and underneath the ionization potential in volts.

1 H 13.6																	2 He 24.6
3 Li 5.4	4 Be 9.3	5 B 8.3	6 C 11.3											7 N 14.5	8 O 13.6	9 F 17.4	10 Ne 21.6
11 Na 5.1	12 Mg 7.6	13 Al 6.0	14 Si 8.1											15 P 11.0	16 S 10.4	17 Cl 13.0	18 A 15.8
19 K 4.3	20 Ca 6.1	21 Sc 6.7	22 Ti 6.8	23 V 6.7	24 Cr 6.8	25 Mn 7.4	26 Fe 7.9	27 Co 7.9	28 Ni 7.6	29 Cu 7.7	30 Zn 9.4	31 Ga 6.0	32 Ge 8.1	33 As 10	34 Se 9.8	35 Br 11.8	36 Kr 14.0
37 Rb 4.2	38 Sr 5.7	39 Y 6.6	40 Zr 6.95	41 Nb 6.8	42 Mo 7.4	43 Tc	44 Ru 7.5	45 Rh 7.7	46 Pd 8.3	47 Ag 7.6	48 Cd 9.0	49 In 5.8	50 Sn 7.3	51 Sb 8.6	52 Te 9.0	53 J 10.4	54 X 12.1
55 Cs 3.9	56 Ba 5.2	57 La 5.6	72 Hf 5.5	73 Ta 6	74 W 8.0	75 Re 7.9	76 Os 8.7	77 Ir 9.2	78 Pt 9.0	79 Au 9.2	80 Hg 10.4	81 Tl 6.1	82 Pb 7.4	83 Bi 8	84 Po	85 At	86 Em 10.7
			58 Ce (6.9)	59 Pr (5.8)	60 Nd (6.3)	61	62 Sa (5.6)	63 Eu 5.7	64 Gd 6.2	65 Tb (6.7)	66 Dy (6.8)	67 Ho	68 Er	69 Tm	70 Yb 6.2	71 Cp 5.0	
87 Fa	88 Ra 5.3	89 Ac	90 Th	91 Pa	92 U 4	93 Np	94 Pu	95 Am	96 Cm								

for instance, in the case of neon (U_i = 21.5 V) about 30,000 °K. On the other hand the gas itself is relatively cold (e.g. <100 °C). Consequently in this discharge only the pairs of processes (1) and (2) are active and owing to the absence of inward radiation there is again no complete equilibrium of radiation. Therefore, as a general rule, the relative intensities of the various spectral lines cannot be deduced from a temperature equilibrium. In the case of a gas mixture the spectrum of a substance with high ionization potential can be entirely suppressed by a substance with a lower ionization potential, owing to the fact that the electron temperature is determined by the component with the low ionization potential, provided, of course, that this component is present in sufficient concentration. A typical example is the sodium lamp which contains neon gas for starting the discharge in the cold state. Upon ignition this lamp gives a red neon light and as the temperature of the lamp rises this light is gradually replaced for the greater part by yellow sodium light, while the electron temperature drops from the high level it assumes in pure neon to a much lower level (about 9000 °K) determined by the sodium.

In the quantitative analysis of gas mixtures with the aid of low-pressure discharges the foregoing has has to be taken into account, so that it can only be used, for instance, for comparing mixtures of about the same composition.

Discharges at high pressure; arc and spark

The arc discharge (discharge of great current density, with thermionic emission of the cathode) in gases of atmospheric pressure is distinguished from the form of discharge discussed above in that the gas assumes a high temperature. This is due to the fact that the elastic collisions (collisions not accompanied by ionization of excitation) between electrons and gas atoms or gas molecules are so numerous that the gas receives a considerable quantity of kinetic energy which can be carried off only by means of thermal conduction and radiation. It may be taken that also in the arc the electrons have a Maxwellian velocity distribution. The electron temperature, however, will be only slightly higher than that of the gas. The condition in the arc is therefore comparable to that in the flame, with this difference that the temperature is usually much higher. Consequently the arc, and particularly the arc between carbon electrodes, is exceptionally suitable as a source of light for spectrochemical analysis: owing to the high temperature of the electrodes almost all substances can be vaporized in the arc, and with the high temperature of the gas also spectral lines of elements with a fairly high ionization potential are made visible.

The suppression of the spectrum of a not readily ionizable element by that of a readily ionizable element also occurs here to a certain extent, because an element with low ionization potential is strongly excited and thus gives a strong radiation, which causes the arc temperature to drop. For quantitative examination where it is desired to produce all the spectra, as far as possible under equal conditions, it is therefore necessary that the substance to be examined should be present in only a small concentration, so that it will not greatly affect the temperature of the arc.

In addition to the arc discharge, also the spark is much used in spectrochemistry. A spark is an instantaneous discharge in a narrow conducting channel formed in the gas between the two electrodes. The conditions in the sparking channel are comparable to those in the arc discharge but the electrodes are for the greater part cold, only the cathode being locally heated to a high temperature. There is extensive literature available about the use of the spark for quantitative analysis ⁵). We shall not go into this here because in this article we wish to confine ourselves to the method where the carbon arc is employed, fed with direct current.

The reasons why the arc is preferred to the spark lie in the following points:

1) Since in the spark method of analysis only very small quantities of the substance are vaporized (0.05 to 0.5 mg), whereas with the arc method 5 or 10 mg is vaporized and brought to emission, the latter method is to be preferred in cases where the material to be examined is not homogeneous (e.g. magnet steel, silicon iron and suchlike).
2) The spark can only be used for special routine analysis with materials having the same antecedents (the degree of hardness of steel, for instance, affects the results of the analysis obtained with the spark as regards the secondary components in this material).
3) The method of arc analysis is more universal since it permits of metals, oxides and compounds in general being analysed in the same way, whereas for analysing non-conducting materials with the spark certain artifices have to be employed.

The carbon arc in air is particularly suitable for this analysis by reason of the fact that the main mass formed by the vapour cloud may be considered to be of a constant composition (O, N and C).

Relation between intensity and concentration

We now have to discuss the important question in how far the intensity of a spectral line observed,

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⁵) See, e.g., W. Gerlach et al, Die chemische Emissions-Spektralanalyse I, II and III, Voss, Leipzig 1936.

as expressed in the blackening of the photographic plate on which the spectrum is photographed, can be taken as a measure for the amount of the respective element in the sample under test. This is a question which resolves itself into two others:

1) Is the concentration of the element in the arc proportional to the amount of that element in the sample?
2) Is the measured intensity of the line proportional to the concentration of the element in the light-emitting gas?

The concentration of the element in the arc is determined by the rate at which the element evaporates out of the sample. Thus it will depend not only upon the amount of the element but also upon other factors, such as the temperature-dependency of the vapour pressure of the sample. Given the same quantity, the concentration in the arc will therefore vary as between one case and another. This difficulty is overcome by arranging for a small quantity of the sample to be fully vaporized in the positive crater. If the duration of the photographic exposure is extended over the time taken for the whole of the sample to evaporate, then every atom in the sample has an equal opportunity to emit light and the intensity integrated by the photographic plate is independent of the aforementioned individual differences in the rate of vaporization. Moreover, if so desired, the vaporization can be retarded (by adding a material that does not readily evaporate, such as quartz) or accelerated (by adding a material comparatively easy to evaporate, such as nickel). Thus the line intensity observed is entirely determined by the (constant) temperature of the arc and by the excitation voltage.

With this method where the sample is brought to complete vaporization the material to be evaporated is in a cavity of the lower electrode functioning as anode, with the cathode placed vertically above it. Under the influence of convection in the gas the atoms move vertically upward, after which they ultimately leave the field of the discharge. This vertical motion is accentuated by some of the atoms being present in the form of positive ions and thus being drawn by the electric field of the arc towards the cathode, where they give off their charge. This results in an accumulation of atoms in front of the cathode, so that in its vicinity, in the so-called cathode layer, the emission of light is stronger than in the rest of the arc. For this reason the light from the cathode layer is not usually used for the quantitative spectral analysis; one places in front of the arc a screen with a horizontal slit through which only the light from the middle of the arc discharge can pass (see *fig. 6*). The cathode light is used only in certain cases, for instance when examining elements which are present in very small concentrations, in which case the lower electrode containing the material to be vaporized is often made to function as a cathode and the slit is omitted.

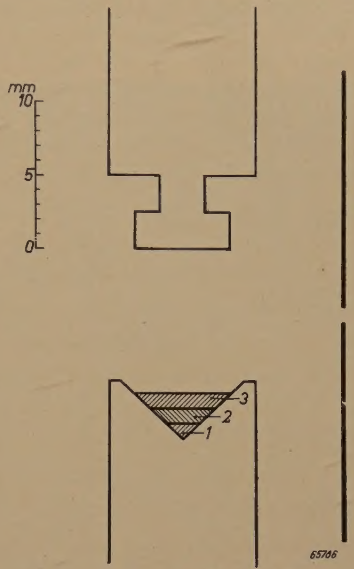

Fig. 6. Arrangement of the electrodes. The lower one, containing the specimen to be vaporized, is usually the anode. On the right the slit though which the light from the middle of the arc is allowed to pass to the spectrograph. In the case of a substance that is not readily vaporized the charge consists of *1* nickel. *2* the specimen, *3* graphite; in the case of a fairly volatile substance the charge is *1* specimen, *2* quartz, *3* graphite. The electrodes have been given their particular shapes to ensure a symmetrical form of the discharge.

We now come to the second question, viz. whether the line intensity is proportional to the concentrations of the atom contained in the gas. Under the conditions just described the same fraction of the element in a certain state of excitation will have been present in the part of the arc used for the analysis, so that one may expect the total amount of energy radiated in a certain spectral line to be proportional to the total number of atoms of that element present in the sample.

There is, however, one disturbing factor, the self-absorption. When a spectral line is formed by the transition from a state *1* to a state *2* then a quantum of emitted light meeting another atom in the state *2* may bring the latter into the state *1*; this atom is then itself capable of emitting a quantum of the same frequency. In this phenomenon, which is also called resonance, there is, therefore, no loss of energy in itself. The quantum of light, however, is retained longer in the discharge and the radiation is reduced, since only the atoms in the outermost layers of the gas can emit their quanta of light unchecked and those in the excited state inside the arc are apt to be destroyed by one of the collision processes (2) or (3).

By a somewhat schematic argumentation this can be explained, for a transition to the ground level, as follows: Let n_0 be the number of atoms in the ground state and n_E the number of excited atoms in a state E. The number of excited atoms formed by collision can then be represented by Cn_0 and the number destroyed by collision by $C'n_E$, whilst the number of emitted light quanta is represented by An_E and the number of excitated atoms reformed through self-absorption by Zn_0, all with reference to the unit of time. In the stationary state

$$n_0\,(C + Z) = n_E\,(A + C')\,.$$

The number of quanta leaving the discharge space per unit of time is:

$$Q = n_E A - n_0 Z \approx n_0\left(\frac{CA}{C'} - Z\right)$$

since $n_E/n_0 \approx C'/C \approx \exp(-E/kT)$.

Since Z is proportional to the density of radiation, which very roughly is proportional to n_0, it follows that to a first approximation Q is a quadratic function of n_0:

$$Q \approx an_0 - bn_0^2\,.$$

The resonance absorption, which always occurs whenever the state *2* coincides with the initial state, increases with the concentration of atoms in the state *2*. Therefore, where the concentration is large, the line intensity will increase less than proportionately with the concentration of the excited atoms and thus the integrated line intensity will no longer be proportional to the total number of vaporized atoms.

In the case of transitions where the final level itself is a high-energy level there is usually little self-absorption. Preferably, therefore, lines situated "high" up in the energy level diagram will be used for the investigation. But this is not always possible. Where it is a matter of determining small quantities of an admixture one is usually restricted to principal lines, which are mostly transitions to the ground level and thus show self-absorption. Below it will be shown how in such a case a correction can be made for the effect of self-absorption.

How the tests are carried out

Fig. 7 shows the apparatus employed for the analyses carried out in the Philips Laboratory at Eindhoven.

As already stated, a weighed amount of the sample (5 mg), if necessary with the addition of an admixture for controlling the evaporation, is placed in the positive crater. The arc is then struck and the spectrum photographed. The distance from the arc to the slit in the spectrograph and the width of the slit (say 0.025 mm) are not varied. Of course the same photographic material is used and the photographic plates are all developed at the same temperature. Fluctuations in the photographic material, which cannot always be avoided even when it is of a perfectly reliable make, are regularly checked by taking special photographs.

After the photographic plate has been developed, fixed and dried the further work is done in two stages:

a) the qualitative examination, and
b) the measurement of the intensity.

In the qualitative examination it has to be determined what elements are present in the sample. In many cases this is known in advance, but then the lines of the various kinds of atoms on the plate have to be identified and those most suitable for measuring have to be picked out. Mostly the lines are identified by ascertaining how the lines are situated with respect to a fixed reference spectrum which is always photographed at the same time on another part of the plate. Mostly one chooses for this the spectrum of the iron arc, the wave-lengths of which are accurately known.

Usually the spectrum is qualitatively examined by placing the plate in an apparatus which projects onto a white screen an enlarged image of part of the spectrum together with the reference spectrum (*fig. 8*).

Let us suppose that a certain line has been chosen for measuring its intensity. The classical method is that whereby the density is measured. The plate is placed in an apparatus by means of which a fine line of light is projected on the photographic picture of the spectral line. With the aid of a photocell and a galvanometer one then determines the quotient of the intensity I that has passed through the photograph of the spectral line and the intensity I_0 that has passed through a part of the plate where there is no image. The quantity $D = \log I_0/I$ is called the density. From this density the intensity has to be determined of the light that caused the blackening. This is done, as is known, with the aid of a number of density marks obtained by exposing the plate to a constant light source, both unattenuated and attenuated in certain ratios (with the aid of a rapidly rotating sector). The density of these marks is plotted against the logarithm of the intensity, thus giving a curve which is characteristic for the kind of plate and the method of developing.

When measuring intensities in this way one has to reckon with the blackening of the background, since in spite of all precautions some scattered light always falls upon the plate and slightly fogs it. This fogging merges with the blackening caused by the line and allowance has to be made for it by separately measuring the background density, preferably close to the line to be measured, and then correcting the line intensity measured for the background intensity. Thus a great deal of labour is involved in this method of measuring intensity and as a consequence it takes rather a long time.

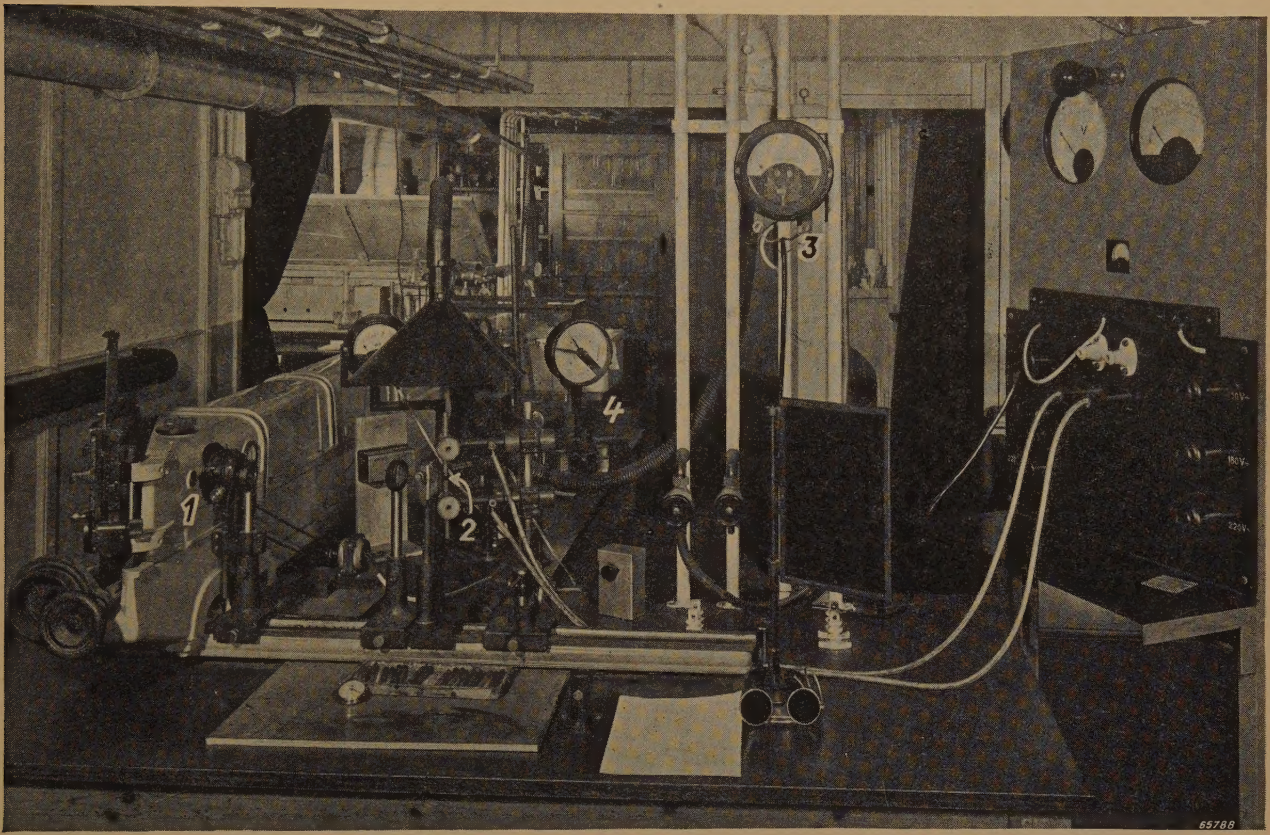

Fig. 7. Photograph of the whole of the apparatus employed for recording the spectra. On the left the automatic quartz spectograph (Hilger E492) with cassette open. On the optical bench at *1* is the spectograph slit, in front of which is a rotating sector and a focusing lens casting the light on the prism; at *2* the carbon arc with the horizontal slit, above which is a suction device. To the left of the slit is an auxiliary lens projecting an image of the arc on a screen beside the spectrograph slit, by means of which the source of light can easily be aligned in the optical axis. Behind this lens is the thermostat keeping the temperature of the room constant at 21-22 °C. At *3* the ammeter for reading the arc current (10 A). At *4* a torsion balance for quickly weighing off 5 mg of material. In the background apparatus for carrying out simple chemical manipulations.

A simplified method has therefore been introduced which saves time, inter alia, owing to the correction for the background density taking place automatically 6).

What is known as an s.p.d. (standard paper density) scale — a strip of white paper bearing a number of density marks produced on it photographically — is laid on the horizontal white screen (fig. 8) onto which the spectrum is projected for the qualitative examination. The density marks on this s.p.d. scale are a number of lines which in width and sharpness resemble the spectral lines as projected onto the screen, these lines being obtained by a photographic process whereby their reflection density D^r (the logarithm of the ratio of the reflection of the white paper and of the density mark) is made to increase in equal steps (about 0.025). The weakest line has a density of about 0.075 (84% reflection) and the darkest about 0.375 (52% reflection). These lines are numbered from 1 to 13. The scale is shifted along the screen until the projected image of the spectral line to be measured is flanked by two successive lines of the scale, such that the density to be measured lies between the flanking densities. The density of the projected image can then be expressed in a number of the scale, and after some practice divisions of a step can be estimated.

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6) See also N.W.H. Addink, Spectrochimica acta 4, 36—42, 1950 (No. 1).

Not only does this combine the qualitative with the quantitative test into one process, but at the same time it gives automatically a correction for the background density. This can be explained in the following way: Let the density of the projected line image on the white paper of the scale (logarithm of the ratio of the brightness of the white paper illuminated respectively through the non-exposed and through the exposed plate) be D_{l+b}, where l refers to the line and b to the background. The density of the line appears to correspond to a certain mark s on the scale. This mark, however, is illuminated by light which has passed through the fogged part of the negative beside the line, so that its density is $D^r_s + D_b$ (by the logarithmic definition the densities are additive). When the background density is not too intensive it has been found from experience that D_{l+b} may be replaced by $D_l + D_b$. By equation we get:

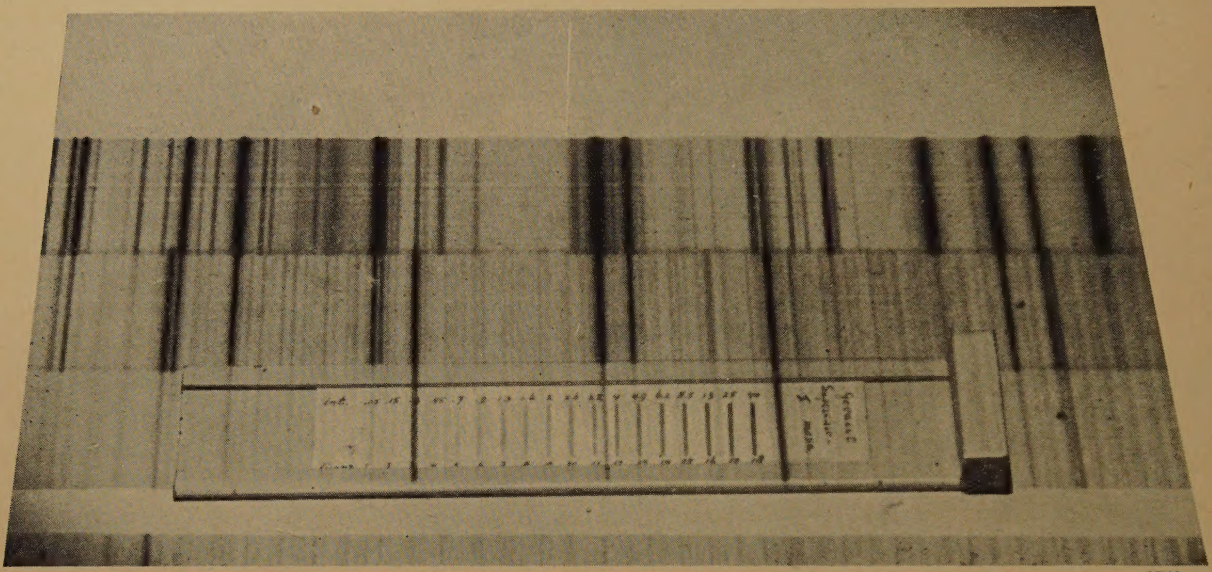
$$D_l + D_b \approx D_{l+b} = D^r_s + D_b ,$$

or

$$D_l \approx D^r_s .$$

Thus we get by direct means approximately the density, D_l, of the line **without** background density! All that is needed is to establish the relation between the number of the s.p.d. scale and the intensity of the spectral lines to be measured, by means of a scale of density marks on a photographic plate, and this need be repeated only now and again to check the constancy of the plate material.

Once the line intensity has been determined a relation has to be found between that intensity and the amount of the element concerned contained in the sample. This is done empirically by starting with specimens of known composition.



65700

Fig. 8. The screen on which a magnified image of the spectrum is projected and upon which the s.p.d. scale is laid.

This does not imply that the spectrochemical analysis is entirely dependent upon the chemical analysis. In fact the concentration can be determined entirely spectrochemically by the method of addition. One adds to the sample containing an unknown quantity ($c = x$) of an element, different known quantities ($c - x = m, n, ...$) of the same element, and the intensities derived from the densities found are then plotted as functions of the quantities added. When the line connecting these points (see *fig.9)* is extrapolated to zero intensity the quantity sought is found directly along the (negative) abscissa [7]).

Different spectral lines will be chosen according to the quantity under examination, since it is preferred to have the reflection density on the screen lying in the interval 0.1—0.3 (50—80% reflection), because there the contrast sensitivity of the eye is greatest.

Where just one single measurement is to be taken the work entailed in the calibration of the scale takes more time than the actual measuring, but this is of no consequence in the case of routine examinations where a large number of analogous cases have to be investigated and the same calibrated scale can be used for them all.

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[7]) See N. W. H. Addink, Rec. trav. chim. Pays-Bas **67**, 690—696, 1948; **70**, 155-167, 1951 (No. 2).

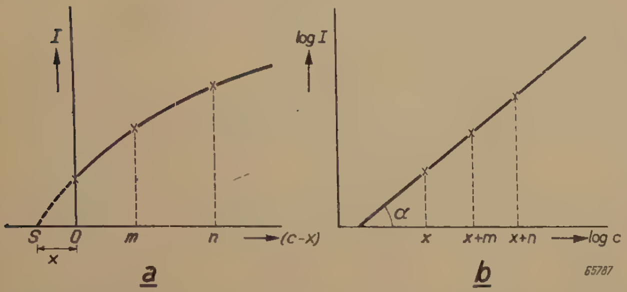

Fig. 9. Explanation of the additive method for determining concentrations.
a) By plotting the intensity I as a function of the amount added $(c-x)$, after extrapolation the point S is found. The distance SO is the unknown concentration x.
b) As a check the concentrations c as found from (*a*) are plotted logarithmically against the logarithm of I, when a straight line should be obtained with $\tan\alpha = n \leq 1$.

Correction for self-absorption

We shall consider briefly the manner in which self-absorption finds expression in this investigation. As already remarked, one will try to avoid this by measuring lines high up in the energy diagram.

If there is no self-absorption there must be proportionality between the intensity measured and the amount of the element contained in the sample. When the intensity is plotted on a logarithmic scale against the logarithm of the concentration one finds a linear relation with a slope 1:1 (45°). Where there is self-absorption the lines as a rule still show an approximately linear relation between the logarithm of the intensity and the logarithm of the concentration, but with a slope <1, which shows that in that case the simple formula $I = kc$ does not hold and that instead we have the empirical equation

$$I = k'c^p, \text{ where } p < 1.$$

Once the value of p has been determined for a certain line, from tests with known concentrations of a certain element, this can be used for analysing an unknown sample containing that element.

Examples

To give some idea of the degree of accuracy reached, some examples are given of analyses that have actually been carried out.

The first example concerns a chromium-nickel steel. Three entirely independent analyses were carried out, with the following results:

	Fe	Cr	Ni	total
	69.5	19.4	9.7	98.6
	71.3	17.8	9.5	98.6
	71.6	18.1	9.5	98.6
Average	70.6	18.4	9.6	98.6
SD_{rel}	0.8	2.5	1.0	

The figures are percentages by weight; at the bottom of each column the average of the figures in that column is given and underneath that the relative standard deviation from the average as a percentage of the average, thus:

$$SD_{rel} = \frac{100}{y_m}\sqrt{\frac{\sum (y-y_m)^2}{N(N-1)}},$$

where y is the measured value and y_m the average of a column ($N = 3$).

The total time taken for the analysis (carried out by one person) was 2 hours.

The next example relates to a magnet steel. For each element two values are given, each being the average obtained from four spectra recorded on one plate, whilst also the average of these values is given. For comparison the result of a chemical analysis is likewise shown in a separate column and the last column gives the relative percentage difference (Δ) between the chemical and the spectral analyses.

		spectr.	chem.	Δ
Fe	48.7 - 49.0	48.8	48.9	0.2
Co	24.1 - 23.5	23.8	24.4	2.5
Ni	15.2 - 15.4	15.3	15.0	2
Al	8.1 - 8.1	8.1	8.0	1
Cu	2.9 - 2.9	2.9	2.9	0
Ti	0.82 - 0.82	0.82	0.82	0
Si	0.17 - 0.17	0.17	0.16	
Mn	0.115 - 0.11	0.11	?	
	total	100.0	100.2	avge 1

The relative standard deviation from the average for one determination for the various elements is 0.5 to 3% (average 2%). In order to reach a relative standard deviation of 1% four determinations are necessary. Four analyses, if carried out by one person alone, take 3 hours and 20 minutes.

As a third example may be mentioned the case of carbonates of earth alkalies of the probable composition 40% $BaCO_0$, 35% $SrCO_0$ and 25% $CaCO_0$. The relative standard deviation for these three components amounted respectively to 2, 1 and 4%.

Since no great accuracy was required these analyses were carried out in duplicate and took in all 90 minutes.

Finally the spectrochemical analysis of a glass is given, and for comparison the result of a chemical analysis of the same sample.

	Spectrochemical	Chemical
SiO_2	70.8	70.6
Na_2O	0.2 ± 15% rel.	0.16
K_2O	1.1	0.97
Li_2O	0.9	0.87
B_2O_3	26.3	25.8
MgO	0.008	not determined
Fe_2O_3	0.04	0.05
TiO_2	0.02	not determined
As	0.01	not determined
F	not determined	0.52

Summary. As an introduction to a description of the method of spectrochemical analysis applied in the Philips Laboratory at Eindhoven, the ways in which a spectrum can be formed are considered. It is discussed in turn how atoms are excited by electrons of constant energy (experiments by Franck and Hertz), in a cavity with a constant temperature (King's furnace), in a flame, in electric discharges at low pressure (Geissler tube) and in electric discharges at high pressure (spark and arc). It is explained on what grounds preference is given to the D.C. carbon arc. The specimen to be analyzed is completely vaporized in this arc and a constant part of the integrated radiation is recorded in the form of a spectrum on a photographic plate. The qualitative test (identification of the lines) and the quantitative test (measurement of the density of the lines) are performed simultaneously with the aid of an instrument projecting the spectrogram onto a screen. The density to be measured is related to a scale of density marks on white paper (the standard paper density or s.p.d. scale). One of the advantages of this method is that a correction for the background intensity of the spectrum is made automatically. The s.p.d. scale is calibrated once for all with the aid of densities on a photographic plate caused by known intensities. In many cases the intensity proves to be proportional to the amount of the element investigated. In the case of lines showing self-absorption the relation can be represented by a simple empirical equation. The absolute relation between intensity and concentration is established experimentally once for all. Finally some examples of analyses are given relating both to metals and to non-metals (e.g. oxides, glasses, salts), with figures for the accuracy and the duration of the analysis.

THE SYNCHROCYCLOTRON AT AMSTERDAM

III. THE ELECTROMAGNET

by F. A. HEYN*).

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The huge electromagnet needed for a cyclotron is undoubtedly what in this apparatus appeals most to the imagination of the layman. A favourite demonstration for visitors is to switch on the magnetic field and to let them feel for themselves the great magnetic forces in the cyclotron by giving them an iron rod or a copper ring to hold in their hands.

There is not much to be found in technical literature about the construction of electromagnets, so that it is not merely on account of its imposing dimensions that a more detailed treatment of the construction of a cyclotron magnet seems to be worth while.

Introduction

The most important data of the Philips synchrocyclotron that has been installed in the Institute for Nuclear-physical Research at Amsterdam have been given in the first article of this series [1]). It may be recalled that this apparatus accelerates deuterons until they attain an energy of 28 million electronvolts, and that this is reached by applying an alternating voltage of about 14,000 volts (peak value) between the two dees in the accelerating chamber.

The second article [1]) gave a description of the oscillator, supplying this voltage with a frequency of $\omega/2\pi = 10.7$ Mc/s, and of the modulator, which brings about a periodical reduction of this frequency by about 4%, so that the particles spiralizing outward may be kept in resonance with the accelerating voltage in spite of the inevitable decrease of the magnetic flux density towards the edge of the magnetic field and the relativistic increase of mass.

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[1]) F. A. Heyn, The synchrocyclotron at Amsterdam, I. General review of the installation, II. The oscillator and the modulator, Philips Techn. Rev. 12, 241-247 and 247-256, 1950/51 (No. 9), further referred to in this article as I and II respectively.

We shall now describe the magnet supplying the powerful field in which the dees are situated and which constrains the accelerated particles to follow circular paths. An attempt will be made to explain on what grounds the magnet has been given its particular shape and dimensions and how these have been determined. After dealing with the construction of the magnetic circuit we shall discuss the construction of the exciting coils and the cooling system.

Fundamental considerations for the design of the magnet

The basic point was the energy to be given to the particles, which had been fixed at 25 million electron volts. For deuterons with this energy the classical formula for kinetic energy $T = \frac{1}{2}\, mv^2$ (v = velocity, m = mass of the deuterons $= 3.35 \times 10^{-27}$ kg) can be applied with sufficient accuracy for our purpose, and with the aid of the resonance condition ($\omega = v/\varrho = eB/m$, see I) it follows directly that:

$$T_{\mathrm{MeV}} = \frac{10^{-6}e}{2m}\,(B\varrho)^2, \quad \ldots \quad (1)$$

where e is the elementary charge $= 1.6 \times 10^{-19}$ coulomb, ϱ is the radius of the orbit in metres, B the flux density in weber/m^2 at the orbit.

When particles are required with a certain energy, according to the formula the product BR is fixed, R being the radius of the largest orbit described by the particles between the pole faces. From $T = 25$ MeV it follows that $BR = 1.015$ Wb/m. R is always smaller than the radius r of the poles of the magnet, because, as will be explained later, the edge of the magnetic field cannot be used on account of the greatly reduced value of B obtained there. Mostly R is 80 to 90% of r, as was already known from other cyclotron magnets. Taking $R = 0.85\ r$, Br must be 1.2 Wb/m. Actually B is here the flux density on the orbit R, but as a first approximation it may be assumed that the flux density is of the same value in the whole of the space between the magnet poles.

Another important factor for the design of the magnet is the distance d between the poles. This is first of all determined by the height to be given to the dees in order to get the greatest possible beam current (see I). Further, the distance between the dee to which the high voltage is applied (the other dee is earthed) and the covers of the accelerating chamber must not be too small, so as to be sure that there can be no risk of flashover and that also the capacitance will not be too high between this dee and earth (see II). Finally, there must be space enough for the auxiliary apparatus, i.a. for the ion source. Therefore we started by considering a value of $d = 36$ cm.

Having fixed Br and d, in order to form some idea of the magnet required we can calculate what magnetic energy is needed in the air gap. This can be determined with the aid of the formula

$$W_m = \tfrac{1}{2}\, B\, H\ (\text{air gap volume}), \quad . \quad . \quad (2)$$

where $H = B/\mu_0$ is the magnetising force 2). Hence:

$$W_m = \frac{1}{2}\,\frac{B^2}{\mu_0}\cdot \pi\, r^2\, d = \frac{\pi}{2\mu_0}\,(Br)^2\, d,$$

which, after substituting the values $Br = 1.2$ and $d = 0.36$, yields:

$$W_m \approx 650{,}000 \ \text{joules}.$$

What this figure means may be imagined when it is said that the magnetic energy in the air gap of a powerful moving coil loudspeaker is about $^1/_4$ joule.

The problem of how to get a magnetic field with the desired values of Br and d is governed in part by technical considerations but more so by economic considerations.

For various technical reasons a small pole diameter $2r$ should be chosen, thus a high flux density B is required. The dee is then not excessively heavy, this being of importance because its weight has to be carried by a transmission line which can be supported by ceramic insulators only at a considerable distance from the dee (see II); the capacitance of the dee is limited; the dimensions of the (evacuated) accelerating chamber are also kept small, so that it can withstand better the force of the atmospheric pressure, there is less risk of vacuum leaks and less trouble from occluded gases. Against these advantages a high flux density B is uneconomical, as we shall presently see. Only in the case of very large synchrocyclotrons will the compromise between B and r be determined more by the technical considerations, since with a very large value of r the technical difficulties become almost insurmountable.

As regards the economic considerations we have

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2) The reader is reminded that in the system of rationalized Georgi units used here the permeability of air (or vacuum) $\mu_0 = 4/\pi 10^7$ henry/metre.

to distinguish between the capital outlay and the running expenses. Under the running expenses, apart from the salaries of the operators, it is mainly the power consumption and cooling water that are of importance; in fact, the whole of the energy converted into heat by the dissipative resistance of the exciting coil has to be carried off by a water-cooling installation. Coming under the capital outlay is, among other items, the cost of this cooling installation and that of the converter supplying the direct current required. The smaller the necessary electric energy is kept the lower are these costs. But by far the biggest item in the capital outlay is the cost of the amount of steel [3]) required for the magnetic circuit and the copper for the coil. If the electric power is to be kept small then the copper of the magnetising coil has to be of a large cross-sectional area, thus involving a very large amount of copper, and since the closed magnetic circuit must leave space enough for the coil to be built into it, the more we try to limit the dissipated power the more steel is needed.

Thus it is seen that the power to be chosen must be a compromise between running expenses and capital outlay. In this connection it is very instructive to consider for a moment the possibility, in principle, of reducing the cost of electricity and water entirely to zero, namely by employing a permanent magnet! A simple calculation will show that this "compromise" is certainly not the optimum. Under idealized conditions the following formula holds for a permanent magnet [4]):

$$\tfrac{1}{2}B_{\mathrm{air}} \times H_{\mathrm{air}} \times \text{volume of air gap} = \\ = -\tfrac{1}{2}\, B_{\mathrm{steel}} \times H_{\mathrm{steel}} \times \text{volume of magnet steel.} \quad (3)$$

On the left we have again the magnetic energy in the air gap, W_m, and on the right that in the magnet steel. The product $B_{\mathrm{steel}} \times H_{\mathrm{steel}}$ depends very much upon the kind of steel and the working point on the B-H curve, which is determined by the form of the circuit and its antecedents. With a modern magnet steel, viz. "Ticonal" 2A (there are still better steels but these are much more expensive), the product can be at most about —15,000 joules/m^3 (i.e. -1.8×10^6 gauss oersted); taking into account, i.a., the leakage, in practice one may perhaps reckon on a value of —10,000 joules/m^3. Taking the value of W_m = 650,000 joules we thus find that the permanent magnet would have to contain roughly 130 m^3, or 1000 tons, of magnet steel! Owing to the expensive alloy components and the complicated manufacture the cost of magnet steel is many times that of "ordinary" steel suitable for an electromagnet, and for the electromagnet of our cyclotron it appeared that we could manage with "only" 200 tons of this steel. Obviously, therefore, even if it had been possible to overcome the inherent technical difficulties [5]), the use of a permanent magnet could not be considered.

Now let us turn back to the question of the power to be chosen for the electromagnet. The necessary compromise between capital outlay and running expenses will, of course, be greatly affected by the local rates charged for electricity and water and by the prevailing prices of the (electrolytic) copper and steel needed. As to the latter costs it may be noted that for a given power it is possible to design constructions using a large amount of steel but requiring comparatively little copper, and vice versa. There is an optimum quantitative ratio of steel to copper, which in turn is affected by the relation between the quality of the steel and its price. Quality is a function of the B-H curve of the steel. The better the quality, the less the quantities of steel and of copper required for a given dissipative power.

Thus it is evident that it is a rather complicated matter to find the construction most favourable from the point of view of economy. In our case the problem was simplified by the fact that a converter was already available with a power of more than 80 kW, which is of the same order as was used for other cyclotrons for about the same particle energy. Further, there was no alternative as regards the quality of the steel, since only one type of steel was available [6]). Thus our problem was reduced to the question of the optimum quantitative ratio of steel to copper for the given power and the given quality of steel, and how the magnetic circuit and the magnetising coil had to be dimensioned so as to get that optimum ratio.

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[3]) According to the new nomenclature, all grades of iron now used as constructional material, also the soft "iron" of an electromagnet, have to be classified as steel (the criterion is the occurrence of an α-γ transition, and not, as before, a minimum carbon content).

[4]) See A. Th. van Urk, The use of modern steels for permanent magnets, Philips Techn. Rev. **5**, 29-35, 1940. — The minus sign in the equation is due to the fact that in the case of a permanent magnet H_{steel} is always opposite to B_{steel} ("demagnetising force").

[5]) The permanent magnet would have to be magnetised after it has been installed, and this would entail the building of an enormous auxiliary coil and installation for activation which would only be used once. Further, the fact that a permanent magnet cannot be temporarily "switched off" for carrying out work on the accelerating apparatus, etc. would have led to very great complications.

[6]) The properties and the manufacture of this kind of steel were described some time ago in this journal: J. J. Went, Philips Techn. Rev. **10**, 246, 1948. It is to be added that further insight subsequently obtained into the specific requirements that have to be answered by the steel for our cyclotron has shown that the steel in question could have been given still more favourable properties (a higher magnetic saturation) without involving any extra cost; the castings had, however, already been made.

With the converter available an upper limit was set to the current I and the voltage V of the magnetising coil, namely about 175 A and about 500 V. It is important to note that this restriction in the choice of I, for a given power, is no impediment in reaching the optimum ratio mentioned above, since the magnetic field in a given magnetic circuit is determined only by the number of ampere turns, nI, and with a given product nI the volume of copper required for the coil is not primarily influenced by the further choice of n and of I. If a low value is chosen for I (thus n large) then for the given power $W = r_k I^2$ the resistance r_k of the coil can be high, whilst if a high value is chosen for I (n small) r_k must be small, and it appears that for this reason the cross-sectional area of the copper for the large number of turns in the first case may be chosen so much smaller than that required for the few turns in the second case that the total volume of copper (provided the average length per turn is the same) works out equal for both cases.

Even if the said limits in the choice of I and V had not already been fixed by the converter available, from the point of view of dependability we should have been obliged not to choose too high a voltage across the coil, since it is imperative to exclude the risk of breakdown in the coil, having regard to the amount of work that would be involved if this part of the installation should need repairing. It is only with a comparatively low voltage that this dependability can be guaranteed without excessive insulating material being required in the coil, that is without causing the "copper factor" of the coil (percentage of copper in the total volume) to drop too far below 100%.

On the other hand, a much lower voltage and higher current than the given values of about 500 V and 175 A could not be chosen either, because higher currents would lead to rather exceptional constructions of the direct-current generator and, moreover, the correspondingly very small resistance r_k of the coil (even in our case this had to be limited to about 3 ohms) is apt to entail all sorts of constructional difficulties (influence of contact resistances, irregularities in the generation of heat, etc.).

Procedure in designing

General layout of the magnet

The general layout of the electromagnet to be designed follows from some obvious considerations. The magnetic field in the air gap must above all be uniform and symmetrical with respect to the centre plane, so that it is necessary to have two coils, one on either side of the air gap. The two cylindrical poles around which the coils are placed exercise a powerful force upon each other (in our case, as may be calculated, about 2 million newton, corresponding to a weight of about 200 tons); the mechanical distortion must nevertheless be small and in any case symmetrical so as not to affect the field adversely. In particular, the pole faces must be kept exactly parallel. Finally the space between the poles must be easily accessible for mounting the accelerating apparatus proper. The shape of the magnet as drawn in *fig. 1* satisfies all these requirements. In this sketch the magnet has been drawn to scale in the shape that was ultimately chosen and the actual dimensions are given. It was of course the determination of these dimensions that constituted the main task in the designing of the magnet, bearing in mind the aforementioned object of obtaining the desired field with the most favourable compromise as regards the volume of copper and the volume of steel needed.

The calculations for the magnet are based upon the equation:

$$nI = \oint H \, \mathrm{d}l \, , \qquad (4)$$

according to which the magnetomotive force, i.e. the line integral of the magnetising force along a line of magnetic force (or along an arbitrary closed line enclosed by all the turns) is equal to the number of ampere-turns required to produce the magnetising force. The integral can be split up into one part belonging to the path that has to be traversed in the course of the integration in air — in our case the pole distance d — and two other parts belonging to the path of integration in the two poles and to that in the yoke closing the circuit, thus:

$$nI = \left(\int H \, \mathrm{d}l\right)_{\mathrm{air}} + \left(\int H \, \mathrm{d}l\right)_{\mathrm{poles}} + \left(\int H \, \mathrm{d}l\right)_{\mathrm{yoke}} . \qquad (5)$$

The idealized case

The magnetising force in the air gap being $H = B/\mu_0$, for the air term the number of ampereturns required is:

$$(nI)_{\mathrm{air}} = B \, d/\mu_0 \qquad (6)$$

Since the air term — and here we are anticipating what follows — will form 70 to 80% of the total (this percentage is called the "efficiency" of the magnet), for a first approximation we may ignore entirely the steel terms (taking the reluctance of the steel circuit to be zero) and ask what value

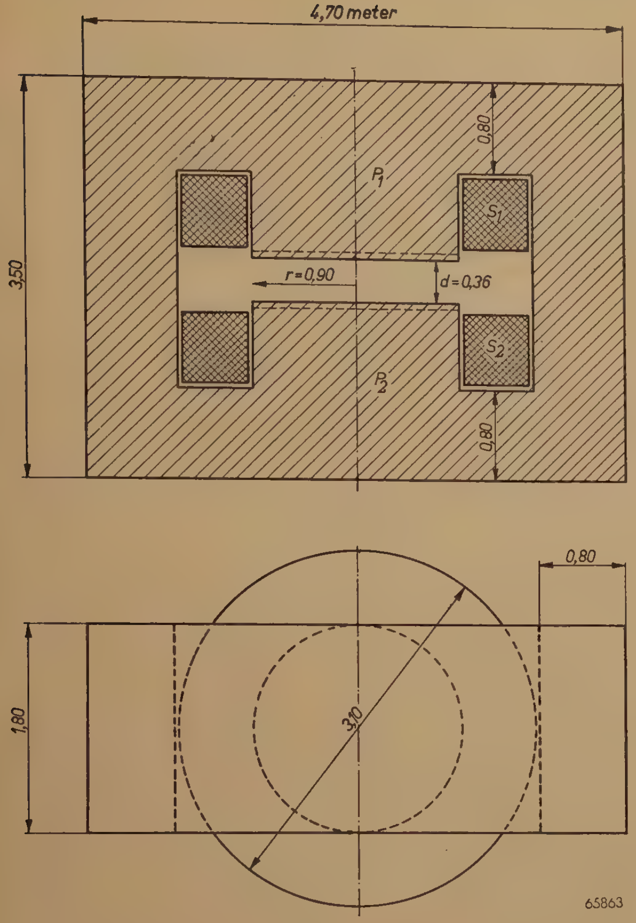

Fig. 1. Form of the electromagnet of a synchrocyclotron, in cross section and top view. Around each of the poles P_1, P_2 is an annular coil (S_1, S_2).

The space between the poles is actually subdivided into three parts. The accelerating chamber is placed between the poles with an air gap of 2 cm on top and underneath; the thick steel covers at top and bottom of this chamber have to be reckoned as belonging to the poles. For the sake of simplicity in the drawing the three air gaps have been combined into one; where mention is made of the "pole distance" in the text this is to be taken as meaning the length of this resulting air gap.

of B, or, since the product $Br = 1.2$ Wb/m is fixed right from the outset, what pole radius r will answer the most favourable compromise to which we have repeatedly referred.

It can now be seen why a compromise is necessary, from what follows. The larger the pole radius r, the larger is the average length of copper per turn, but owing to the reduction of B the necessary $(nI)_{\text{air}}$ is smaller (eq.(6)). As a simple calculation will show, the amount of copper initially required diminishes with increasing r and above a certain value of r — in our case already above $r \approx 1.2$ m — becomes independent of r (and also practically independent of the, still variable, pole length, which is equal to the height of the coil; see fig. 1). At the same time however — assuming, in the first instance, that the cross section of the circuit is of the same size everywhere and that the circuit lies as close as possible round the coil — the quantity of steel required rapidly increases with the value of r. When r is very large a constant amount of copper but more and more steel is therefore needed, whilst with a very small r less and less steel suffices (in this approximation) but the quantity of copper required rapidly increases owing to the large value of B. Taking into account the prices of copper and steel we found for the total costs of materials a flat minimum between $r \approx 0.6$ and 1.0 metre, that is to say with B between 2.0 and 1.2 Wb/m^2. The number of ampere-turns then needed for the air term is between 600,000 and 350,000, and thus the optimum in question lies within this range — still ignoring the reluctance of the steel.

In view of the technical considerations mentioned in the beginning of this article we should like to choose the smallest r within the optimum range ($r = 0.6$ m), but when we come to take into account the reluctance it is just on this low side that the range narrows down considerably. The fact is that this reluctance makes it necessary to have more ampere-turns, thus additional copper, and the more so the greater the flux density in the steel, i.e. the smaller the pole radius chosen; consequently with smaller r the amount of copper rises more steeply than in the ideal case. The question is to what value of r does the optimum range now still extend?

It is important to realize that this question cannot be answered exactly, for the following reasons.

Difficulties arising when taking into account the reluctance

The answer to this question amounts to a calculation of the two steel terms in eq. (5). For this we have to use first the condition that the magnetic flux — disregarding for a moment the leakage — must be of the same value in any cross section (surface A) of the circuit, thus

$$B_{\text{steel}} \cdot A_{\text{steel}} = \text{constant} = B_{\text{air}} \cdot \pi r^2 \quad ; \quad . \qquad (7)$$

and, secondly, the relation between the flux density B and the magnetising force H in the steel, which is given by:

$$B = \mu_0 H + J(H) \quad . \; . \; . \; . \; . \qquad (8)$$

where J is the intensity of magnetisation, which depends upon H according to a function empirically determined for each type of steel.

From these equations it is possible, in principle, to determine the value of H in any point of a chosen circuit, and thus the line integral (eq.(4)) for different values of the pole radius can be calculated. Actually, however, there is a relatively large uncertainty about this calculation. In the first place equation (7) holds only to a very rough approximation: near the free ends of the poles a considerable part of the magnetic flux leaves the steel laterally and the lines of force join outside the circuit. This leakage, which occurs at any flux density and depends upon the dimensioning, can hardly be calculated at all and has to be estimated or found empirically (see, e.g., the article quoted in footnote [4]). In the second place the intensity of magnetisation J as a function of H shows the well-known phenomenon of saturation. With high values of H, where the maximum possible magnetization J_s is approached and thus the J-H curve becomes flat, small variations in B, caused for instance by a small variation of the respective cross section A in the experimental design, involve great changes in the magnetising force H required, and of course this renders the calculation hazardous. Furthermore, near the corners of the steel circuit (fig. 1) and particularly near the transition from the yoke to the round pole, the flux density B is by no means constant over the whole cross section of steel, and we do not know exactly what "effective" value of B one has to use here. Moreover the extent to which the point of saturation of the steel is approached also affects the stray field — a larger percentage of the lines of force leave the steel the more this becomes saturated — and this influence can be still less exactly calculated. Finally, the trend of the J-H curve near the point of saturation is highly dependent on small variations in the manufacture of the steel; differences in this respect were in fact observed in some of the blocks of steel from which our magnet was built up.

Closer determination of the pole radius to be chosen

Owing to the uncertainties mentioned it is not possible to predict exactly how the total cost of materials will work out as a function of the pole radius r, but nevertheless we can arrive at a closer determination of the minimum radius required by the following simple reasoning.

Once the intensity of magnetisation of the steel has reached its maximum value J_s the flux density B can be increased further only by raising the term $\mu_0 H$ in eq. (8), just as is the case in the air gap. Then the steel may be said "to behave as air". The corresponding part of the line integral, $\int H_{\text{steel}}\, dl$, which is always very small for small flux densities, then rapidly increases and consequently a large number of ampere-turns are needed for this part. To avoid this the construction has to be such that the magnetic saturation J_s is nowhere too closely approached in the steel.

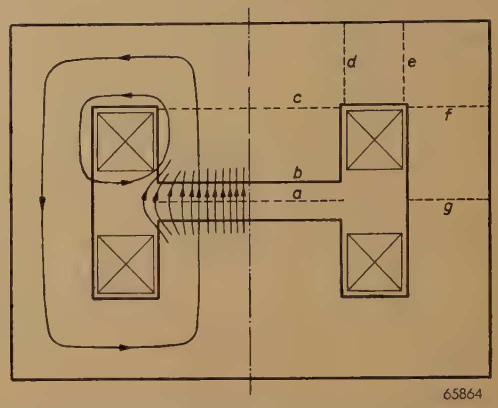

Fig. 2. The flux density considered more closely in various cross sections (a-g) of the steel circuit. The lines of force in the left half of the diagram are indicated very schematically.

In this respect the cross section c in *fig. 2* was to be considered as the most dangerous part. It is easy to predict that the most dangerous place will anyhow lie in the poles: any increase of the cross section — the means of reducing the flux density and thus J — works out more expensive in the poles than elsewhere in the circuit; of course thicker poles require more steel, but they also cost more copper because the average diameter of the turns is larger, and so still more steel is needed because the increased outer diameter of the coil requires a greater length in the horizontal parts of the yoke. In all the existing cyclotron magnets the flux density is indeed greatest in the poles, mostly at or near c. So we could take as a starting point the maximum permissible value of J for that place, which for the steel that we had available, was 2.0 Wb/m². According to the J-H curve this value is reached when $\mu_0 H = 0.1$ Wb/m², thus the flux density in the cross section c becomes $B_c \approx 2.1$ Wb/m².

In the pole faces, cross section b, and in the air gap, cross section a in fig. 2, the flux is much less than in c, owing to the leakage. From trials with models and from the data of existing cyclotron magnets it was known that the ratio of the flux values in c and a — the leakage coefficient — could be taken at about 1.5. Thus, since the cross sections a and c in fig. 2 are of equal size, it follows that with the steel used the flux density in the gap could not be chosen greater than $B_a = 1.4$ Wb/m². So as to allow for some reserve in case in some blocks of steel J_s should turn out to be lower, we chose $B_a = 1.35$ Wb/m² (giving for $B_c = 2.06$ Wb/m² and for $\mu_0 H_c = 0.07$ Wb/m²). From the prescribed value of the product $Br = 1.2$ Wb/m in the air gap it follows that the radius of the poles has to be $r = 0.9$ m (rounded off).

If a larger value were chosen for r the steell terms in eq. (5) would, it is true, be reduced somewhat, but then, as we have seen, the cost of material for the so much larger air term would remain practically the same up to $r = 1.0$ m and then even increase.

Other dimensions of the circuit

The experiments just referred to were carried out with a simple model built to a scale of 1 : 20. This model and a second one made later to the same scale but in a modified form provided us with the necessary data regarding the leakage, etc. which enabled us to make a choice not only of the pole radius but also of other details in the shape of the circuit.

In the first model various cross sections of the yoke, viz. at d, e and f (in every case it is the total cross section of the two "parallel connected" branches that is referred to here), were made of the same size as the cross section c. Measurements showed that the flux in these cross sections was practically equal to that in c. In the second model (and in the actual magnet) the yoke cross sections mentioned were made larger than the pole cross section c, namely 13% larger, as determined from some experimental calculations. It is true that this costs more steel, but then this is amply compensated by the saving in ampere-turns and thus in copper; a reduction of the flux density by 13%, from 2.06 to 1.825 Wb/m^2, is accompanied by a much greater reduction of $\mu_0 H$, namely from 0.07 to 0.025 Wb/m^2, and this reduction is all to the good considering the great length of the path of integration in the yoke!

As regards the shape of the coil cross section, that is to say the ratio of the height h and the thickness D, this could be decided before the pole radius had been definitely fixed, by virtue of the following considerations. The greater the height h chosen the longer the poles become and thus the more steel and — what is worse — the more ampere-turns are needed, this being partly due to the longer path of integration with high magnetising force and partly on account of the greater leakage, which reduces the "efficiency" of the circuit. Moreover, more steel is then also needed for the vertical parts of the yoke, which, together with the poles, have to be longer; this steel cannot be recovered by placing the vertical parts closer together (as would seem to be possible since the coil thickness D becomes smaller with the greater height of the coil), for the efficiency would then be still further reduced owing to a larger percentage of the lines of force passing direct from the poles to these parts of the yoke. On the other hand, the smaller h is chosen the larger becomes the average radius of the turns placed one over the other (for a given number of ampere-turns). This adverse effect very soon exceeds the saving in ampere-turns obtained with shorter poles, and also the resultant saving in steel is balanced by the extra steel required for the longer horizontal parts of the yoke. Therefore neither very large nor very small coil heights are desirable, and in fact a roughly square coil cross section is the best. Small deviations from this form make little difference in the total cost of material, as proved by experimental calculations. Incidentially it should be added that in these calculations it is necessary to take into account the copper factor of the coil, which differs somewhat for different shapes.

Balance of the ampere-turns

Thus we have sketched in broad outline the considerations underlying the determination of the dimensions of the magnetic circuit. It was on this basis that the second model was built and it was then possible to calculate roughly the number of ampere-turns that each part of the model would require. *Table I* gives the result of the calculation, all figures being converted to the dimensions of the actual magnet, for the desired flux density $B_a = 1.35$ Wb/m^2 in the air gap and also for the somewhat larger value $B_a = 1.40$ Wb/m^2. By way of explanation it has to be added that in the calculation the high flux density $B = 2.06$ Wb/m^2 of cross section c was taken for only one-third of the pole length. At the pole face, cross section b, according to the trial model the flux density is already 20% less than that at c owing to the leakage; here, therefore, the magnetising force in the steel is practically negligible. From the measurements of the flux density taken at various places between c and b in the first model the magnetising force in the pole was assumed to be constant ($B = 55{,}800$ A/m) over one-third of the length, then dropping linearly to practically 0 at the end, so that for two-thirds of the length the average value $H = 27{,}900$ A/m could be taken. The inaccuracy involved in this assumption is quite negligible compared with the sources of uncertainty contained in the calculation itself, to which ample attention has been devoted in the foregoing pages.

The efficiency that could be expected from this

Table I. Balance of ampere-turns required for the second model of the magnet (converted to the actual dimensions) according to data in respect to leakage obtained, i.a., from the first model.

Part of circuit	Length in m	$B_a = 1.35$ Wb/m²					$B_a = 1.40$ Wb/m²				
		B Wb/m²	$\mu_0 H$ Wb/m²	H A/m	nI A	%	B Wb/m²	$\mu_0 H$ Wb/m²	H A/m	nI A	%
air gap	0.36	1.35	1.35	1 075,000	387,000	76	1.40	1.40	1 115,000	400,000	70
$^2/_3$ pole	1.03	—	0.035	27,900	57,000	11	—	0.05	40,000	82,000	14.5
$^1/_3$ pole	0.513	2.06	0.07	55,800			2.10	0.1	80,000		
yoke	5.5	1.825	0.015	12,000	66,000	13	1.86	0.02	16,000	88,000	15.5
Total					510,000	100				570,000	100

balance of the ampere-turns, viz. 76%, may be said to be quite satisfactory.

Measurements taken with the second model showed that the assumptions previously made in regard to the leakage agreed well with the actual values. Thus it was not surprising that the calculated number of ampere-turns was found to agree fairly well with the number required in the actual model in order to get the desired flux density in the air gap. The figures are given in *table II*. The model was found to require slightly fewer ampere-turns than was expected.

Table II. The total number of ampere-turns required to obtain the flux density B_a in the air gap. The figures in parentheses denote the efficiency.

B_a Wb/m²	nI calculated	nI measured on second model (converted to actual dimensions)	nI measured on the magnet as constructed
1.35	510,000 (76%)	470,000 (80%)	497,000 (78%)
1.40	570,000 (70%)	527,000 (74%)	548,000 (73%)

From the measurements with the second model it further appeared that 6% of the flux encompasses the individual coils (see the lines of force sketched in fig. 2; the flux through g is 6% less than that through f). This is a considerable amount but not enough to warrant any appreciable increase of the distance between the vertical parts of the yoke.

Now we can pass on from the design to the construction of the magnet and the magnetising force obtained.

A few points in the foregoing rough outline of the design procedure call for further explanation. In particular there is the question of the definite choice of r when taking into account the reluctance of the steel. The pole radius was chosen large enough for the intensity of magnetisation in the dangerous cross section c to reach just the maximum permissible value. Then it was assumed, almost as a matter of course, that the pole is just as thick at the pole face (cross section b) as in c, but this is not a necessity, for the poles could be made conical. In b the flux is 20% less than in c owing to the leakage; with a conical shape of the pole it is therefore possible for the intensity of magnetisation, though relatively increased in b, to be still below the maximum through the whole of the pole. The question therefore arises whether a conical shape, given the same flux density B_c in the cross section c (radius r_c), is advantageous. Suppose for a moment that we reduce the cross section b (radius r), which originally had the value of $r = 0.9$ metre, and that there is then no change in the leakage factors 1.25 and 1.5, which indicate how much the flux in cross section c of the steel is greater than that in b and a respectively. In that case $B_c r_c^2 = 1.25$, $B_b r^2 = 1.5\ B_a r^2$. For the desired energy of the particles $B_a r$ is already fixed, thus $B_c r_c^2 = \text{const.} \times r$, and so, with B_c given, the radius r_c (inner radius of the coil!) could be reduced in proportion to $\sqrt{r}$. In this way we could go to about $r = 0.6$ metre (this limit of the optimum range of r is in fact not appreciably affected by a conically shaped pole); r_c may then be reduced to about 0.75 m. This would indeed mean a considerable saving in steel and copper. Unfortunately the assumption made above is not quite correct: with the conical shape the flux in b and a will be relatively smaller because with this shape of pole — and also on account of the greater average flux density in the pole — there is increased leakage. So little remains of the expected advantage that it does not justify the complications of a construction with conical poles.

What may yield a real advantage is to depart from another tacit assumption, viz. that the whole of the magnetic circuit should be made of one and the same kind of steel. For the most critical parts of the poles, at the cross section c, we could use a more expensive kind of steel, alloyed with cobalt, which increases the magnetic saturation of the steel. This would have meant an appreciable saving in ampere-turns, which might amply have compensated the additional cost of the steel, but, as already stated, at that time there was only one kind of steel available to us.

Of course it is still more advantageous to use a better grade of steel for the whole of the magnet, provided it is not much more expensive. Measurements taken with a more recent model practically identical to the second one referred to above but made with a grade of steel which at present could be considered for the purpose, with a slightly higher saturation, showed that for $B = 1.4$ Wb/m² in the air gap no more than 484,000 ampere-turns will be needed (efficiency 84%!).

The magnet as constructed

Apart from small deviations from the assumed leakage and other inaccuracies in the calculation, the fact that for the second model fewer ampere-turns were needed than had been calculated is presumably due also to the chance circumstance that the steel, especially that in the poles, happened to be of a somewhat better quality. Of course the quality of the steel might also have turned out rather less satisfactory than anticipated, particularly since the annealing of large blocks is different from that of small ones, and this possibility had to be considered as well. Further, defects in the finishing may result in the occurrence of clearances between the blocks of which the magnetic circuit is composed, which raise the reluctance of the circuit. In order to meet such contingencies, in the dimensioning of the actual magnet the copper volume was chosen for a 5% larger number of ampere-turns than calculated from the second model. Afterwards this was indeed found to be quite necessary, as may be seen from the last column of table II.

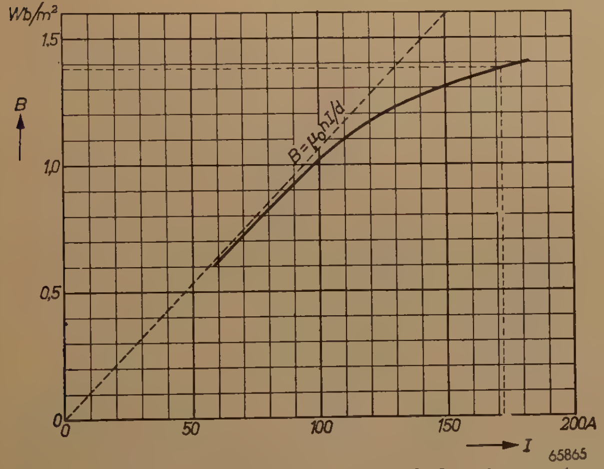

Fig. 3. Flux density B in the centre of the air gap (cross section a in fig. 2) as a function of the excitation current I, as measured on the magnet constructed. The broken straight line, $B = \mu_0 nI/d$ (eq. (6)), is what would be obtained if the reluctance (line integral $\int H\,\mathrm{d}l$) of the steel were negligible.

Fig. 3 represents the flux density B obtained in the air gap of the actual magnet (thus really B_a) as a function of the excitation current I. The coils were made with a total number of 3048 turns, with which the flux density B = 1.35 Wb/m² is reached at a current I = 163 A, so that nI = 497,000. The measures that have to be taken to get a suitable radial field distribution in the air gap (the "shimming"; see below) result in a reduction of the flux density in the axis. This effect, however, was more than compensated when it was found possible to increase the excitation current without the coils becoming too hot (with the cooling capacity available). Thus we can work quite well with an axial flux density B = 1.38 Wb/m². This value was therefore taken as basis for fixing the oscillator frequency, which of course has to be so chosen that the deuterons are brought into resonance with the electric field: $\omega = eB/m$. With the stronger excitation a particle energy of 28 MeV could be reached, instead of the 25 MeV for which the apparatus had been designed (see eq. (1)).

For the resonance to be maintained it is essential that B and thus the excitation current should be kept highly constant. The stabilizing device that was made for this will, it is hoped, be described in another article, as also the safety installation necessary in the event of a sudden failure of the excitation current; unless special precautions are taken, the rapid disappearance of the enormous magnetic flux might give rise to tremendous over-voltages in the coils.

The shimming of the field

For the cyclotron or synchrocyclotron to function properly it is necessary to focus the beam of particles in the centre plane of the air gap. This has already been fully discussed in this Review [7]. For the efficient focusing the magnetic field below and above the centre plane must have a radial component such that the pattern of the lines of force is barrel-shaped. Such a field is obtained automatically as a result of the leakage; the vertical component B of the flux density thereby decreases with increasing radius ϱ — see the dotted curve in *fig. 4a*. Normally, according to this curve, when ϱ is small the relative gradient $(1/B)\mathrm{d}B/\mathrm{d}\varrho$, which may serve as a measure of focusing, is very small, in fact too small for the desired focusing action, whilst with a large radius ϱ it rapidly increases, so much so that an inconveniently large frequency variation of the oscillator would be needed to keep up with the decreasing angular velocity of the particles reaching this zone, whilst we should still have to be satisfied with a relatively small maximum radius R of the orbit (low final particle energy). By placing on the pole faces suitably shaped steel correcting plates and rings, called "shims", the field variation $B(\varrho)$ can be so influenced as to make the gradient answer our purpose better. We aimed at getting an average gradient of 0.02% per cm and keeping this as constant as possible from the axis to the edge of the poles. The shims employed to attain this object, the dimensions of which had to be determined empirically, are represented in fig. 4*c* (not drawn to scale). The result of this shimming is indicated by the fully-drawn lines in figs 4*a* and *b*, from which it is seen that up to a radius of 75 cm the gradient is practically constant, after which it rises very steeply. This means that, when the target is placed in positions corresponding to successively larger values of ϱ, from $\varrho \approx 75$ cm onwards the intensity of the beam will rapidly decrease. In fig. 4*b* the measured beam current i has also been plotted as a function of ϱ, from which it is seen that the maximum useful radius can be taken as $R = 74$ cm. Thus R is 86.5 % of the radius $r = 90$ cm of the poles, and this agrees well with the supposition made in the beginning of this article ($R = 0.85\ r$). With $R = 78$ cm B is about 1.7% smaller than on the axis, viz., 1.355 Wb/m^2, so that the maximum particle energy $T = 28$ MeV is in fact reached. Of course the limit $R = 78$ cm is not sharply fixed. If we are satisfied with a smaller beam intensity a somewhat greater energy than 28 MeV can be reached.

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[7] W. de Groot, Cyclotron and synchrocyclotron, Philips Techn. Rev. **12**, 65-72, 1950/51 (No. 3).

The useful radius R could be slightly increased by making the shims thicker, so that the gradient is kept small up to a larger radius, but in our case this was not possible owing to the space required for the construction of the accelerating chamber, the dees and the accessories.

Owing to the varying degree of saturation in some of the shims the field variation B (ϱ) is dependent upon the excitation current I, as is to be seen from the curves in fig. 4*a*. If I is too small the gradient first diminishes rather steeply towards the edge (fig. 4*b*), possibly even becoming negative, and this would immediately lead to defocusing, causing the beam to disappear. The excitation current must therefore be carefully adjusted to the right value. There need be no anxiety about possible variations while working, since, as already stated, in order to maintain the resonance the current I must anyhow be kept highly constant (to within 0.06%).

It is interesting to consider the radius where the expression $(\varrho/B)\mathrm{d}B/\mathrm{d}\varrho$ reaches the value 0.2. Here the vertical oscillations of the circling particles fall into resonance with the radial oscillations, as a result of which — if the zone with the critical value is not quickly passed — defocusing occurs (see the article quoted in footnote [7]). In our case, at $\varrho = 87$ cm the gradient $(1/B)\mathrm{d}B/\mathrm{d}\varrho \approx 0.15\%$/cm, so the expression referred to above amounts to about 0.12. Roughly speaking, it may therefore be said that in our case the limit set by this defocusing effect upon the energy attainable coincides practically with the limit set by the frequency variation of the modulator being insufficient to compensate the steep decline of B. This coincidence

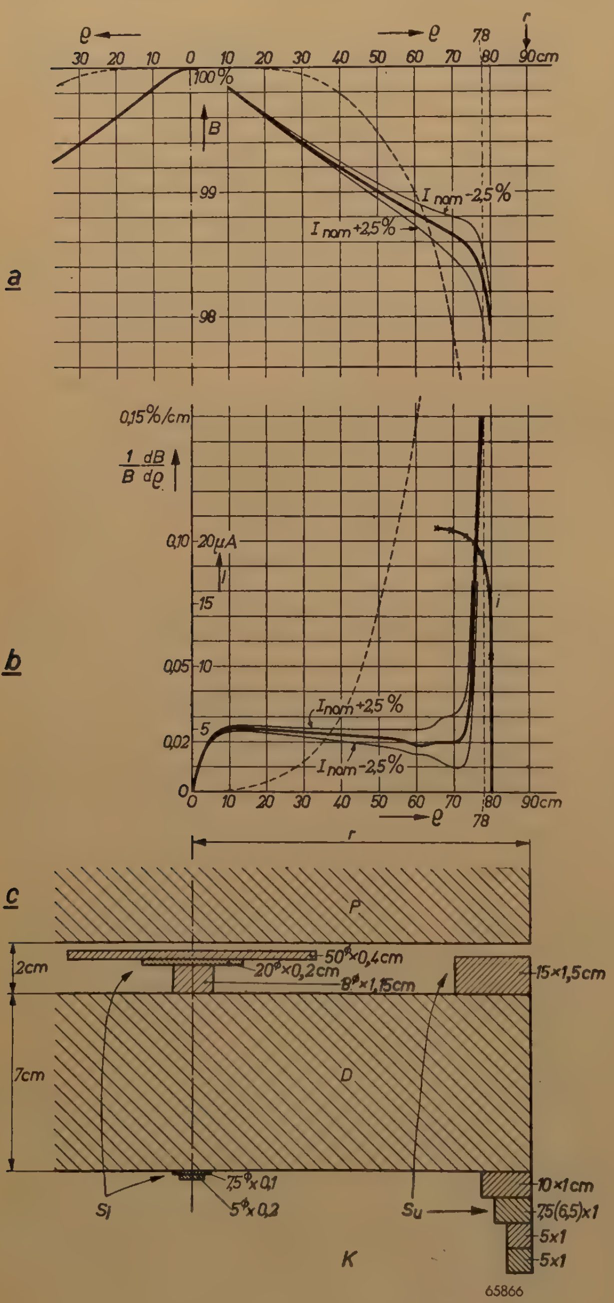

Fig. 4. The shimming of the magnetic field for focusing the particles in the centre plane of the air gap.
a) Variation of the vertical component (as percentage) of the flux density B in the centre plane as a function of the distance ϱ to the axis. Broken line: before shimming. Full line: after shimming. Lightly drawn lines: in the case of the excitation being 2.5% stronger or weaker than normal.
b) The gradient $(1/B)\mathrm{d}B/\mathrm{d}\varrho$ of the curves in (*a*). The measured beam current i (in micro-amperes) at the target is likewise plotted as a function of the distance ϱ from the target to the axis. From $\varrho = 78$ cm onwards the beam intensity drops rapidly. Here the flux density is $B = 1.355$ Wb/m^2, from which follows a maximum deuteron energy of 28 MeV.
c) Cross section of the pole face with the steel shims used for correction. (The other pole is of the same configuration.) For the sake of clarity the heights are drawn to a 10 times larger scale than the widths. P is the pole proper, D the cover of the accelerating chamber K (see fig. 1) which, as far as the thickness of steel is concerned, has to be added to the pole proper; the air gap of 2 cm — costing roughly 40,000 ampere-turns! — was necessary to allow of the accelerating chamber being put into position.
By the combination of central shims s_i the gradient is made to differ perceptibly from zero at a few cm from the axis, while already at 5 cm it reaches the value of 0.02%/cm, which is kept up to about 75 cm from the axis thanks to the shims s_u.

of the two limits ensures that full use is made both of the magnetic field and of the modulator.

Unless counter-measures are taken, the presence of the vertical parts of the yoke causes an azimuthal variation of the field in the gap. This asymmetry can be sufficiently corrected by making the shim ring of 7.5 cm nominal width a little narrower in some places, to as much as 6.5 cm.

Mechanical construction of the magnetic circuit

For the magnet of the dimensions predicted, in this way a total weight of 200 tons of steel was needed. The steel could be supplied only in blocks of at most 15 tons. The yoke was therefore built up of 2 × 4 horizontal and 2 × 4 vertical blocks. The four bottommost blocks were laid on steel girders cast in a concrete foundation, then being levelled off precisely horizontal and at equal height with the aid of packing plates. The blocks for the vertical parts of the yoke were set up on these horizontal blocks and the uppermost blocks were then laid across them (see *fig.* 5). No bolts were used anywhere for fixing these blocks together, their weight being sufficient to keep them in place; there is no need to draw the parts together so as to remove any air gaps between them (see below), since the magnetic forces do this better than is possible by bolting the parts together. Each of the poles was divided into two disks, so that the coils could be put into place (see below). The two disks of the bottom pole were secured with three pins to prevent lateral displacement. The disks of the upper pole were bolted onto the top blocks of the yoke. Although the poles are attracted towards each other by a force of about 200 tons, the bolts need only be calculated to carry the weight of the upper pole, since the magnetic flux determining the force bearing upon a cross section of the circuit is much greater in the cross section *c* (fig. 2) than at the pole faces, cross section *b*. After the excitation current has been switched on the upper pole is therefore drawn up against the top beams of the yoke with a force greater even than 200 tons!

Owing to the force of attraction between the poles, which of course is transmitted as a mutual attraction to the bottom and top beams, the beams tend to bend slightly inward and it would be logical to fear that the vertical beams would thereby be forced outward. The flux through the cross section *f* (fig. 2) however is so great that there the beams are kept

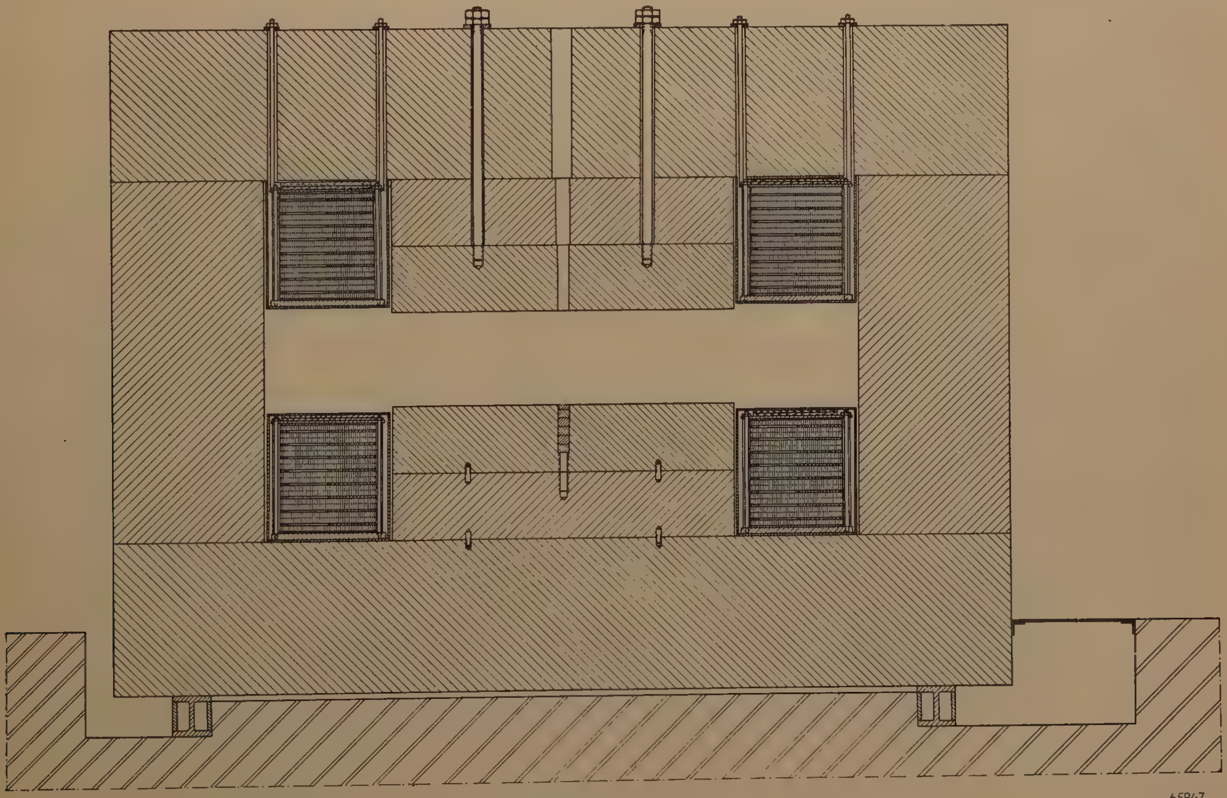

Fig. 5. The yoke drawn here in longitudinal cross section is built up from 2 × 4 horizontal and 2 × 4 vertical steel blocks. Each pole consists of two disks. The aperture in the upper pole, which, like that in the lower pole, was partly filled up before the installation was started up, is necessary for mounting the upper pole and the accelerating chamber.

well together: the deformation of the cross beams is such that their centre line has an inflexion point between the poles and the uprights of the yoke.

Construction of the coils

From the number of ampere-turns $nI = 497{,}000$ and the data of the generator already given in the foregoing it was possible to derive the number of turns required and the cross section needed for the copper. Of course the calculation had to be based on the specific resistance of copper at the working temperature (about 45 °C). Thus we arrived at the number of over 3000 turns already mentioned.

To be able to wind the turns easily and with little force strip copper was used with a section of 0.5 cm × 3 cm. This could be supplied only in rolls of 60 m. For the total length of 24 km (weight about 30 tons) 400 joints had therefore to be brazed. The brazing was done as far as possible mechanically. The joints were made with silver and tested one by one under a tensile force of 500 kg to preclude any risk of breakage after the coil had been made. The strip was bound into what might be called "pancakes" of about 100 turns each on a horizontal revolving table, with two strips of specially strong paper each 250 microns thick interwound as insulation; see *fig. 6.*

Each of the two coils is built up from 16 of these "pancakes" stacked one upon the other. These lie in pairs. The two pancakes of each pair are insulated from each other by two layers of hard paper each 1 mm thick. The pairs are insulated from each other by pieces of resin-bonded fabric 10 mm thick so arranged as to leave a zig-zag path free for the passage of the oil for the cooling (see fig. 8). The pancakes and intermediate plates of each coil were pressed together with the aid of a number of steel plates and tie rods, thus forming a compact ring (*fig.* 7). The bottom coil was placed around the bottom pole, resting on the bottom beams of the yoke and some supporting columns. The top coil was suspended from 16 steel rods screwed into the (locally thickened) clamping plates and passing through notches made in the top beams of the yoke and through six brackets screwed onto the yoke. These rods do not have to carry more than the weight of the coil, since the ponderomotive forces of the magnetic field produced outside the steel by the leakage field force the top coil upwards and the bottom coil downwards.

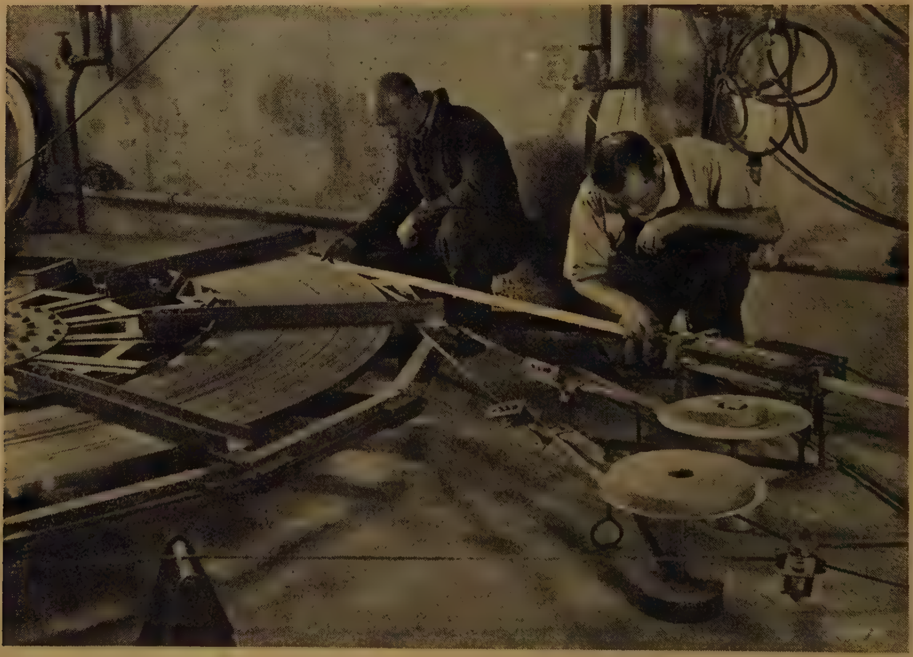

Fig. 6. Winding one of the 2 × 16 "pancakes" from which the excitation coil was built up. The pancake is made by winding a piece of copper strip about 750 m long (cross section 3 cm × 0.5 cm) on a horizontal revolving table, with two layers of paper, fed from two rolls on the right in the foreground, as insulation between the turns of copper. The table was revolved by winding a steel cable round its periphery (seen in the foreground) and then unwinding this cable with an electric winch. The copper strip was kept taut by feeding it through a clamping block with oak facing (500 kg tensile force while winding), seen behind the rolls of paper.

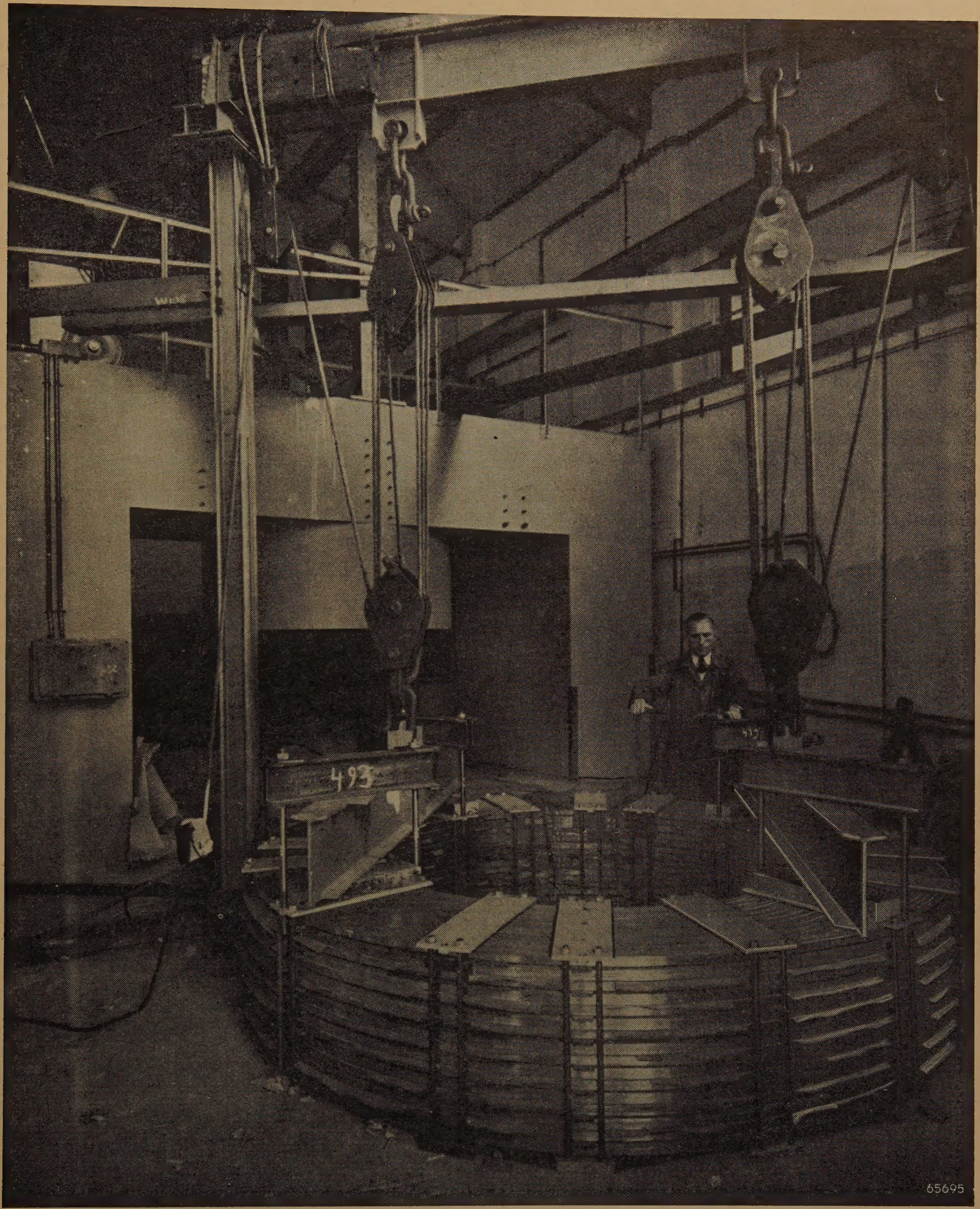

Fig. 7. Completely assembled coil ready to be placed in the tank (fig. 9) and then to be hoisted and put in place round the upper pole of the magnet. See also frontispiece where the two coils have already been placed in position, only the top half of the lower pole remaining to be slid into position and then lowered into place.

Cooling of the coils

The heat (over 80 kW) generated in the copper is carried off by a stream of water, but for the sake of the insulation of the bare windings circulating oil is used as intermediate link. Each coil lies in an annular tank fitting loosely around it, oil being admitted into the tank at two diametrically opposite points. After flowing through the zig-zag channels left between the pancakes the oil runs out through two overflows situated between the inlets (*fig. 8*). The oil in the tanks is not brought under pressure, so as to preclude as far as possible any chance of leakage; it is kept in motion by a difference in height of only a few centimetres between the levels of the inlets and outlets in the tanks. Packing posts of wood placed at intervals round the periphery of the coil inside the tank serve to prevent any "working" of the windings due to ponderomotive forces and at the same time prevent the oil from flowing in any direction other than through the channels. The tanks, which are placed round the coils before the latter are put into place, are not subject to any mechanical load whatever, so that again any risk of oil leaking out through possible capillary cracks is minimized, while nevertheless the steel wall of the tank can be so thin as not to absorb any magnetic flux worth mentioning (*fig. 9*). The tanks are covered with a sheet of tin-plated iron slightly corrugated to prevent mechanical stresses, the cover being soldered on with tin. The hot oil flowing out of the tanks is led into a collecting tank underneath the floor, from which it is pumped through 10 parallel copper pipes around which cooling water is circulated in steel tubes (*fig. 10*). After being cooled the oil flows back into the coil tanks. The consumption of water is 100 litres/min. The oil flows through the cooler and the coil tanks at a rate of 300 litres/min. Good thermal transmission is ensured by arranging for a turbulent flow of both media in the cooler. The difference in temperature between the oil flowing into the coil tanks and that flowing out of them is only a few degrees, since all the oil channels run parallel and the oil traverses only a quarter of the circumference of the coil. It was necessary to have such a short passage for the oil because otherwise we could not have managed with such a small difference in pressure between the inlet and the outlet.

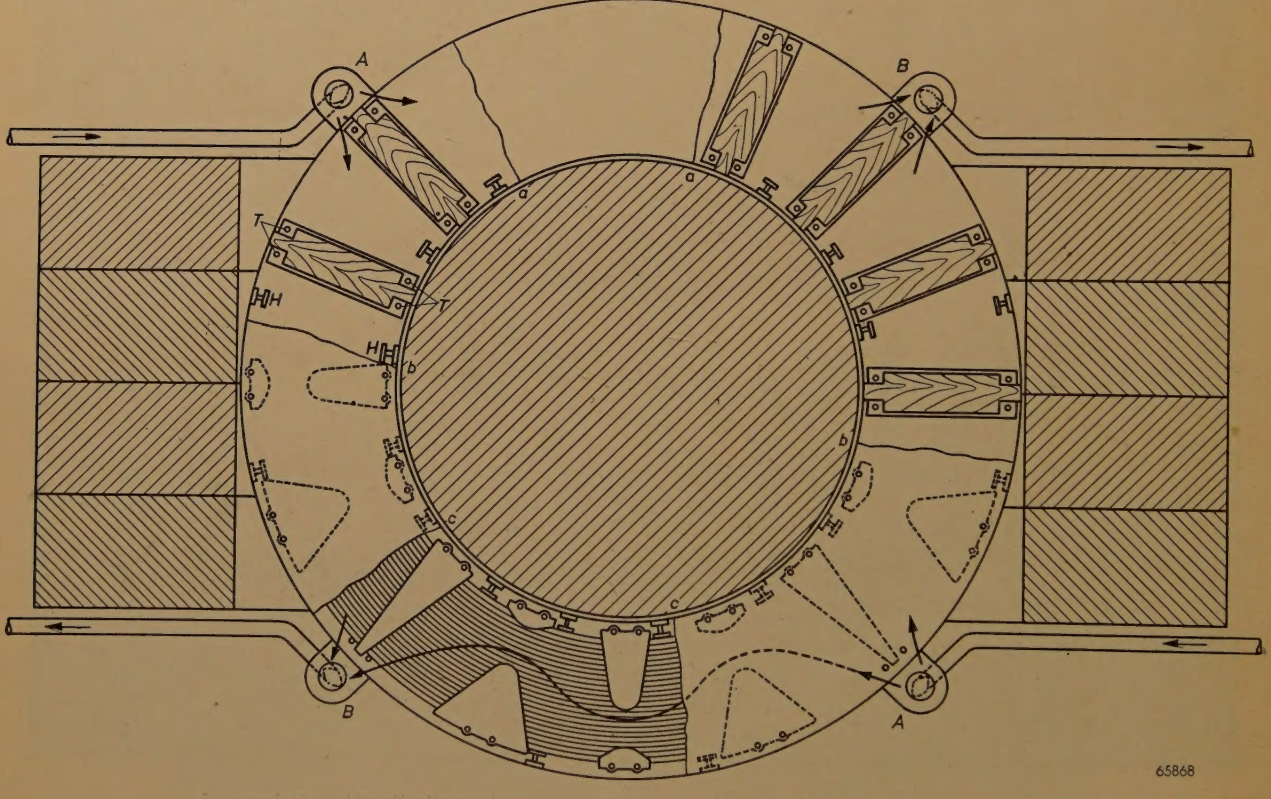

Fig. 8. Top view of one of the coils placed in position in the magnet. From *a* to *b* the cover of the coil tank has been removed to show the wooden boards taking up the pressure of the upper coil bearing against its tank cover or supporting the tank cover of the lower coil; here can also be seen the uppermost of the steel plates with which the 16 pancakes are pressed down on top of each other; *T* are the steel tie rods used for this. From *b* to *c* one looks down onto an insulating layer over the uppermost pancake, and from *c* to *c* this uppermost pancake has been cut away to show the turns of the underlying pancake and the tongue-shaped pieces of resin-bonded fabric guiding the cooling oil along a zig-zag path between the two pancakes. At *A*, *A* the oil is fed into the tank (the 15 oil channels lying one above the other between the 16 pancakes are connected in parallel), at *B*, *B* this oil is carried off, so that the oil traverses only a quarter of the circumference of a pancake. *H* are the packing posts of wood between the pancakes and the wall of the tank.

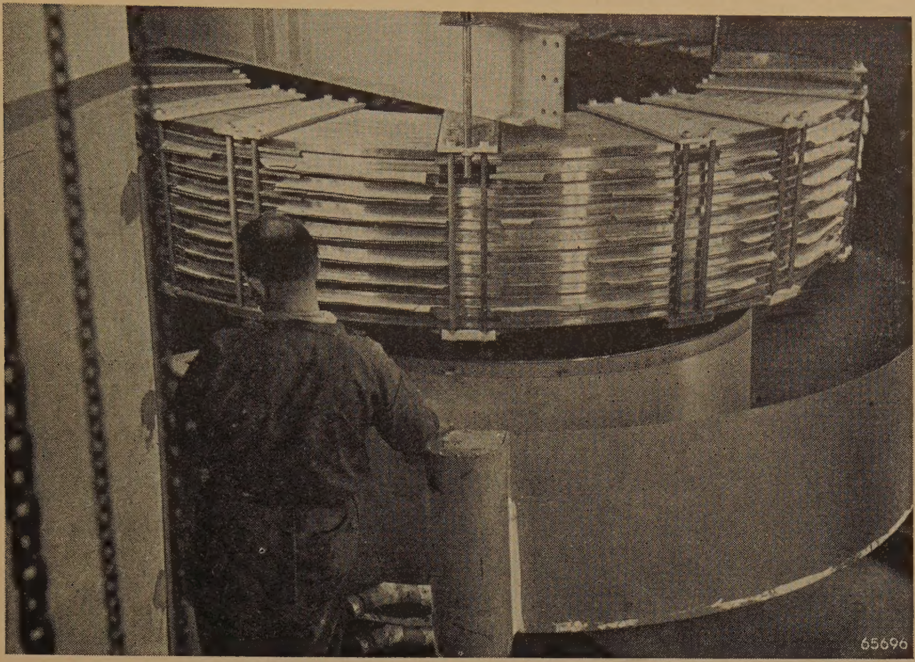

Fig. 9. A coil, consisting of 16 pancakes pressed together, ready to be placed in the annular tank.

The average temperature of the oil reaches a rather high level (about 45 °C). The equilibrium is determined, inter alia, by the decrease in viscosity of the oil with rising temperature — accompanied by an increase in the rate of flow — and by the increased heat transmission to the water with rising temperature of the oil. Since the expected temperature of the coils had already to be known for

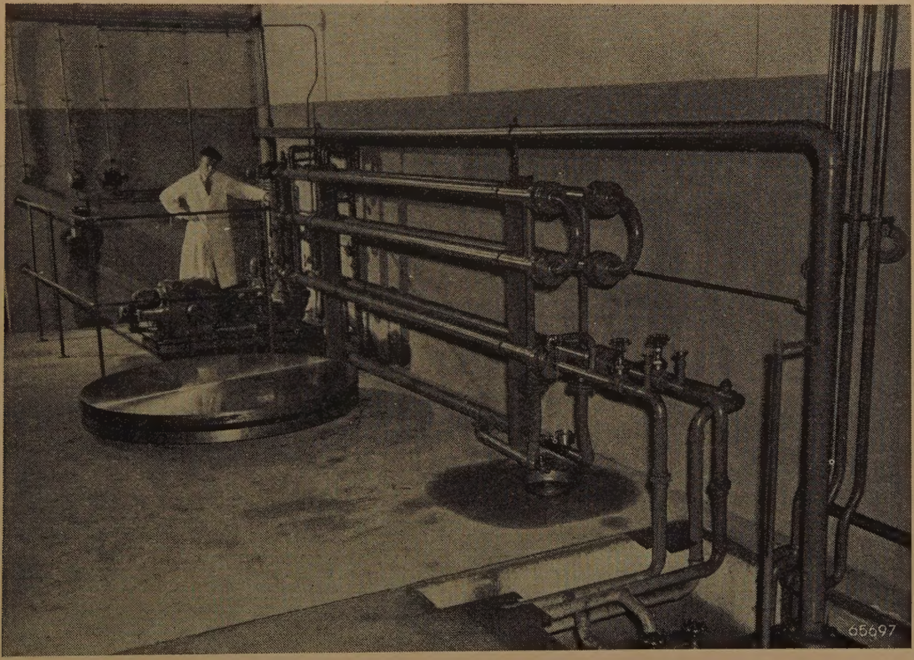

Fig. 10. Cooling plant. On the right in the foreground is the underground collecting tank for the hot oil coming from the coil tanks. The oil is pumped up (pump in the background) from the collecting tank and forced through 10 parallel copper pipes of 2.2 cm diameter and 12 m in length. These pipes are mounted, five at a time, in two steel tubes of 9 cm diameter in which cooling water flows along the oil pipes (100 l/min). These two tubes, seen in the middle of the photograph, are each folded into three horizontal lengths one above the other so as to save space. After having circulated through the cooler the oil flows back into the coil tanks.

calculating the dimensions of the magnet, this equilibrium was previously investigated with experimental models so as to ascertain, in particular, the flow resistance of the channels and the amount of heat that can be dissipated at different rates of flow of the oil.

Owing to the comparatively high temperature of the oil also the thermal radiation of the coil tanks with their large surface contributes considerably to the dissipating of the heat.

Summary. The large magnet of the Philips synchrocyclotron at Amsterdam was designed for accelerating the deuterons to an energy of 25 million electronvolts, using an air gap of 36 cm. It was known that the power for the excitation could be about 80 kW, and a steel with a certain magnetisation curve was available. The magnetic circuit — the general shape of which is prescribed by various technical considerations — had to be so dimensioned as to keep the total cost of steel and copper to the minimum. These optimum dimensions cannot be deduced exactly but have to be found approximately by experimental calculations and measurements taken with models. The most important considerations determining the design procedure are explained in this article. With the dimensions finally chosen — a pole diameter of 1.80 m, a yoke length of 4.70 m and a yoke height of 3.50 m — 497,000 ampere-turns are needed to obtain on the axis of the air gap a flux density of 1.35 Wb/m²; 76% of these ampere-turns are required for overcoming the reluctance of the air gap, the remainder being required for the reluctance of the steel circuit. The total weight of steel used for the magnet is 200 tons and that of copper 30 tons. The magnet has been built up from 16 steel blocks and 4 steel pole pieces, which, with the exception of the upper pole suspended from bolts, have been joined together without any fixing means whatever. The coil, made in two parts, has been calculated for a total voltage of about 500 volts (resistance about 3 ohms, total number of turns over 3000). Each part is built up from 16 "pancakes" of wound copper strip with paper insulation. The pancakes are cooled by circulating oil; the hot oil is pumped into a cooler where the heat is carried off by a stream of water (water consumption 100 litres/min). With the cooling installation constructed it was found possible to use a slightly stronger excitation current for the magnet (coil temperature about 45 °C), so that now the apparatus can be normally worked with a flux density of 1.38 instead of the planned 1.35 Wb/m². In this article the measures are also described by means of which a radial variation of the flux density is reached which is suitable for stabilizing the orbits described by the particles. The largest useful orbit appears to have a radius of 78 cm. Owing to this and the slightly greater flux density, deuterons of 28 MeV can be produced with this synchrocyclotron instead of the planned 25 MeV.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands.

1953: J. M. Stevels: Le fer dans le verre (Verres et Réfractaires **4**, 293-298, 1950, No. 5). (Iron in glass; in French.)

The behaviour of iron in glass is intimately related to the variable valence of the iron atom, which makes electronic transitions possible. In network-forming positions Fe^{3+}-ions cause a brownish colouring, while in network-modifier positions there is practically no colouring. Fe^{2+}-ions seldom occur alone and, if so, mostly as network modifiers, but sometimes also as network formers. These ions do not cause a visible colouring. The bluish-green colour of some glasses containing iron is due to the simultaneous action of Fe^{2+}- and Fe^{3+}-ions.

Indications exist that at least one of these ions (or both) must be present in network-forming positions. The influence of Ti^{4+} is of importance in this respect because this ion shifts the equilibrium between the network-former and the network-modifier positions of Fe-ions in the latter direction.

It may be that decolouring of glass simply means elimination of TiO_2. A further study of the equilibrium $Fe^{2+} \leftrightarrows Fe^{3+}$ in both positions is needed.

1954*: A. Claassen: Titan (Hb. Anal. Chem., Dritter Teil, Band IVb, Springer, Berlin 1950; pp. 1-169).

Report on quantitative analytical methods for the determination of Ti and the various methods of separation.

1955*: A. Claassen: Zirkon und Hafnium (Hb. Anal. Chem., Dritter Teil, Band IVb, Springer, Berlin 1950, pp. 170-287).

Report on quantitative methods for the determination of Zr and Hf and the current methods of separation.

1956: J. L. Snoek: Density variations in aluminium (Phil. Mag. **41**, 1188-1192, 1950, Nov.)

From careful determinations of the density of samples of aluminium in various conditions the conclusion is drawn that grain boundaries in aluminium may have a more spacious structure than is generally assumed. In an addendum the possible influence of gas bubbles (H_2) on the density is discussed.